Long term shifts in Puget Sound: A potential multi-scale systems problem?

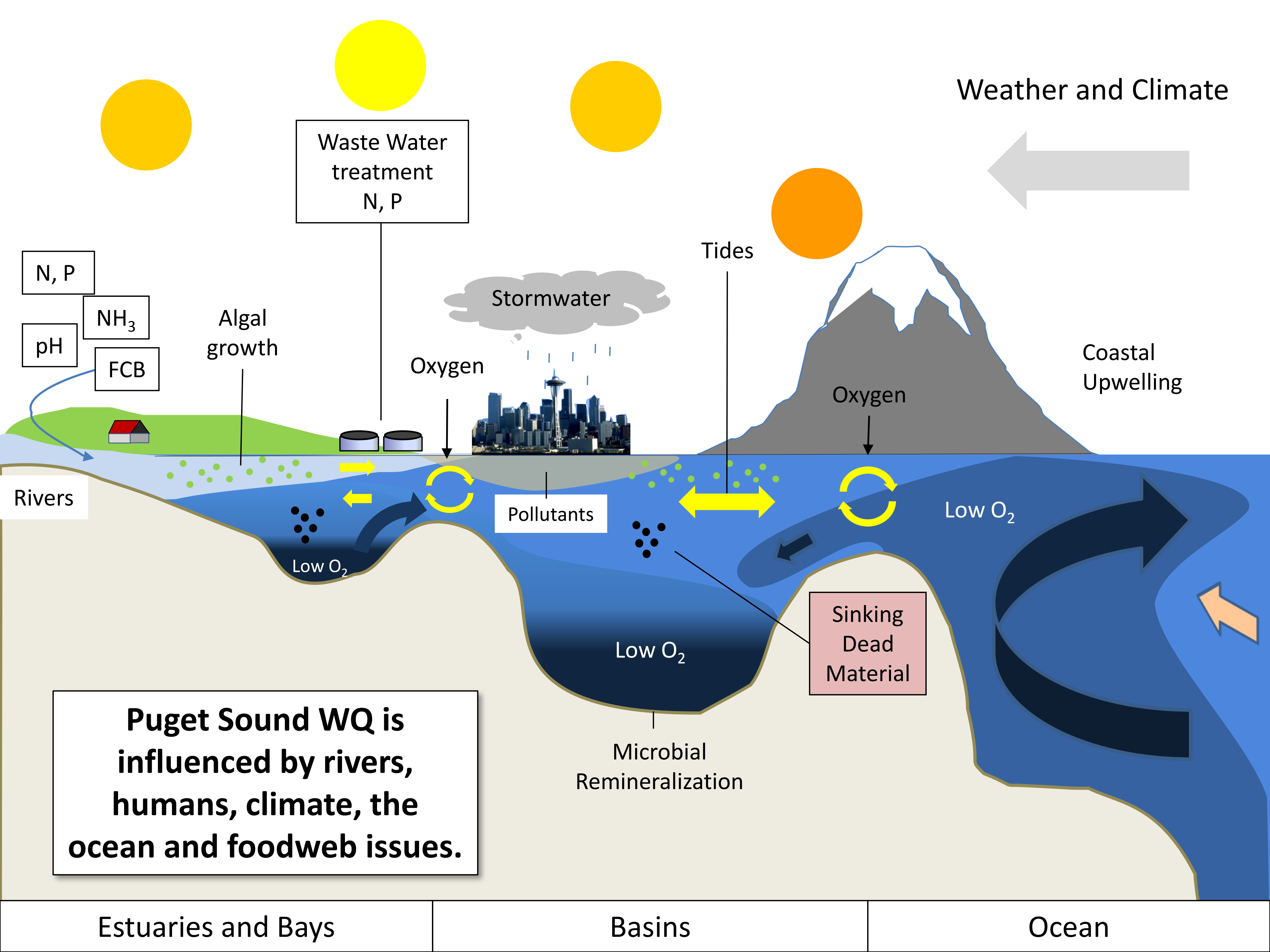
Christopher Krembs, Mark von Prause, Ecology

1. **Growth limiting nutrients are increasing in fresh and salt water.**

2. **Nutrient ratios are shifting in fresh and salt water.**

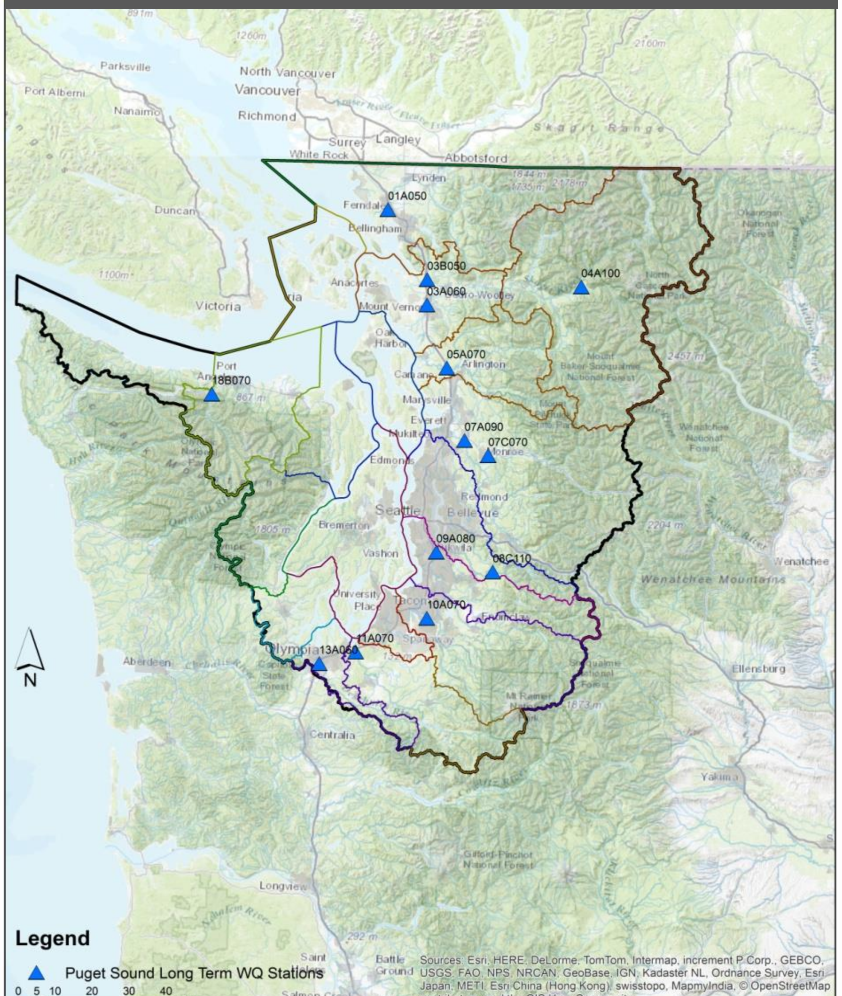
3. **Phytoplankton biomass and composition is changing in the marine systems!**

4. **Motivation to explore shared long-term changes across the marine-freshwater continuum.**


Weather and Climate
Waste Water treatment N, P
N, P
NH_3
pH
FCB
Algal growth
Stormwater
Oxygen
Tides
Oxygen
Coastal Upwelling
Rivers
Low O_2
Pollutants
Low O_2
Low O_2
Sinking Dead Material
Microbial Remineralization
Puget Sound WQ is influenced by rivers, humans, climate, the ocean and foodweb issues.
Estuaries and Bays
Basins
Ocean

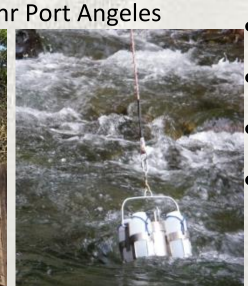
Measuring freshwater quality long-term trends

Greater Puget Sound region



Water Quality variables measured monthly at 13 core river stations

Station	Station Name
01A050	Nooksack R @ Brennan
03A060	Skagit R nr Mount Vernon
03B050	Samish R nr Burlington
04A100	Skagit R @ Marblemount
05A070	Stillaguamish R nr Silvana
07A090	Snohomish R @ Snohomish
07C070	Skykomish R @ Monroe
08C110	Cedar R nr Landsburg
09A080	Green R @ Tukwila
10A070	Puyallup R @ Meridian St
11A070	Nisqually R @ Nisqually
13A060	Deschutes R @ E St Bridge
18B070	Elwha R nr Port Angeles

Discrete Grab Sampling

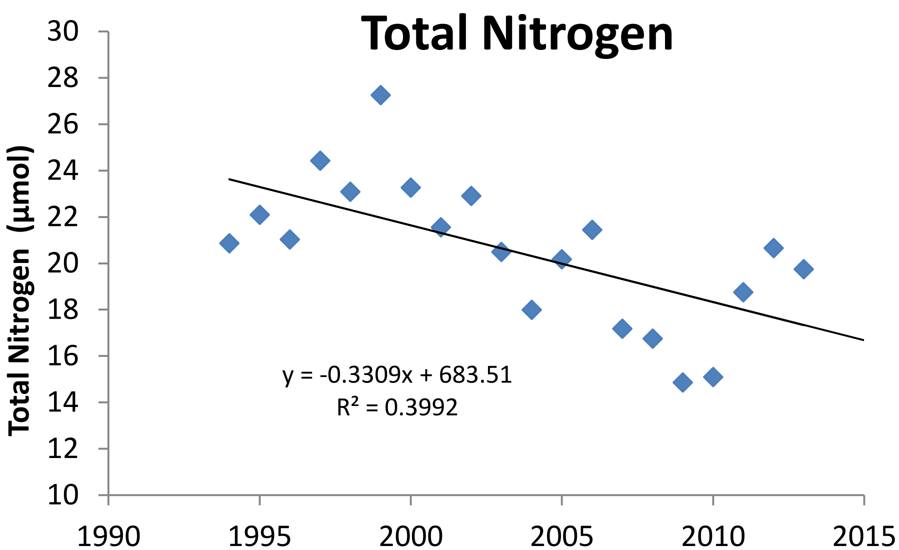
Physical variables

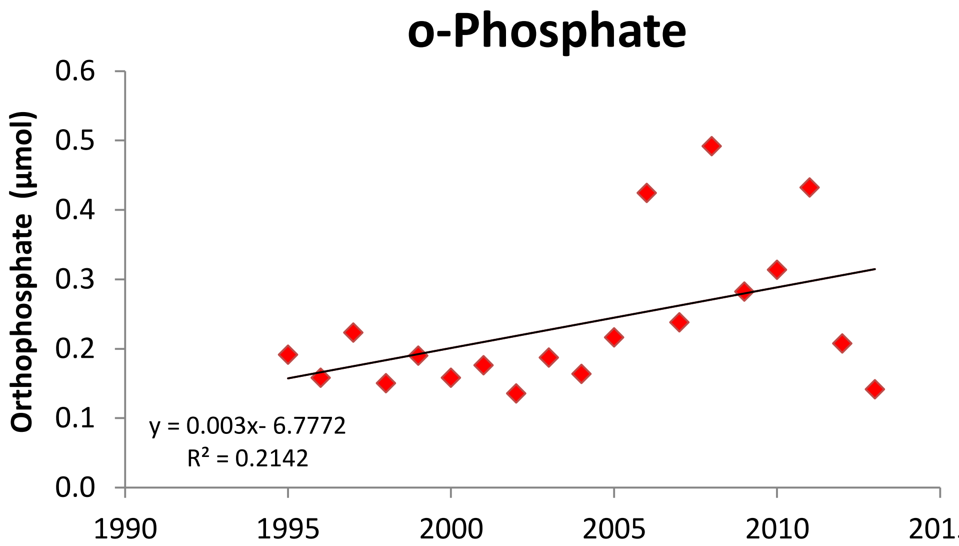
- Temperature
- Flow
- Turbidity
- Suspended Solids

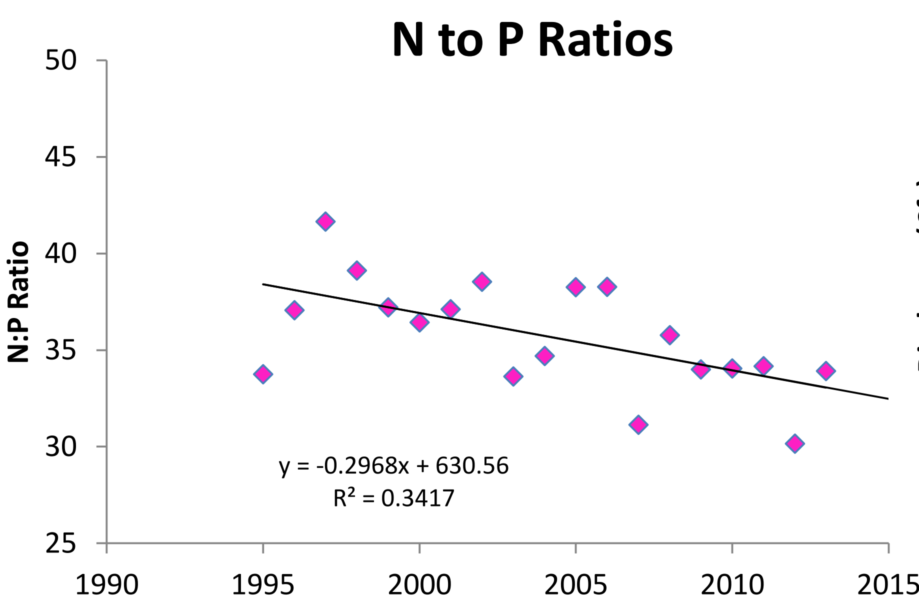
Chemical variables

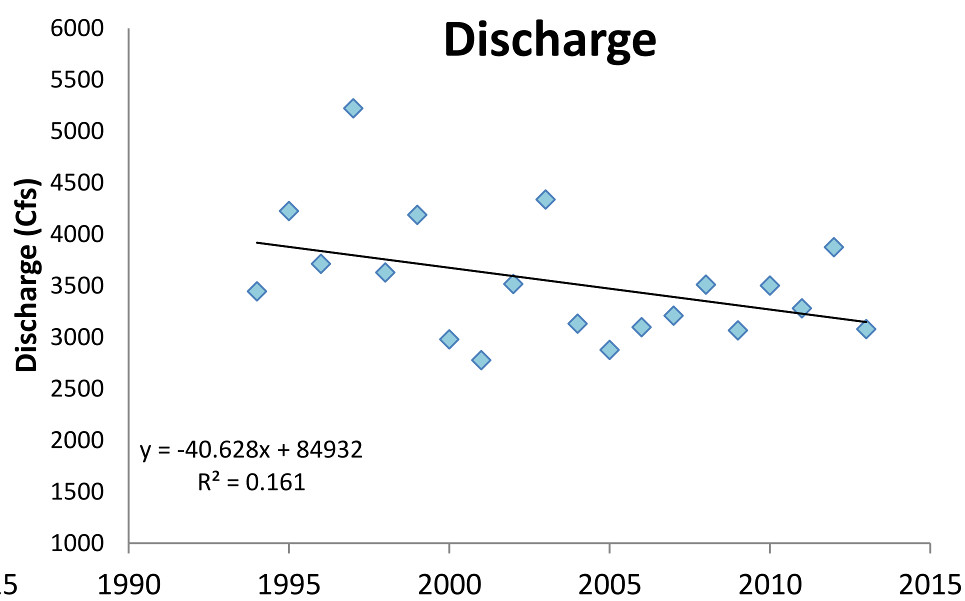
- Oxygen
- Nitrate Plus Nitrite
- Total Nitrogen
- Soluble reactive phosphorus
- Total Phosphorus
- Ammonia
- pH
- Conductivity

Total mean annual trends for total nitrogen, phosphorus, N:P Ratio and discharge at freshwater monitoring locations in the Puget Sound watershed



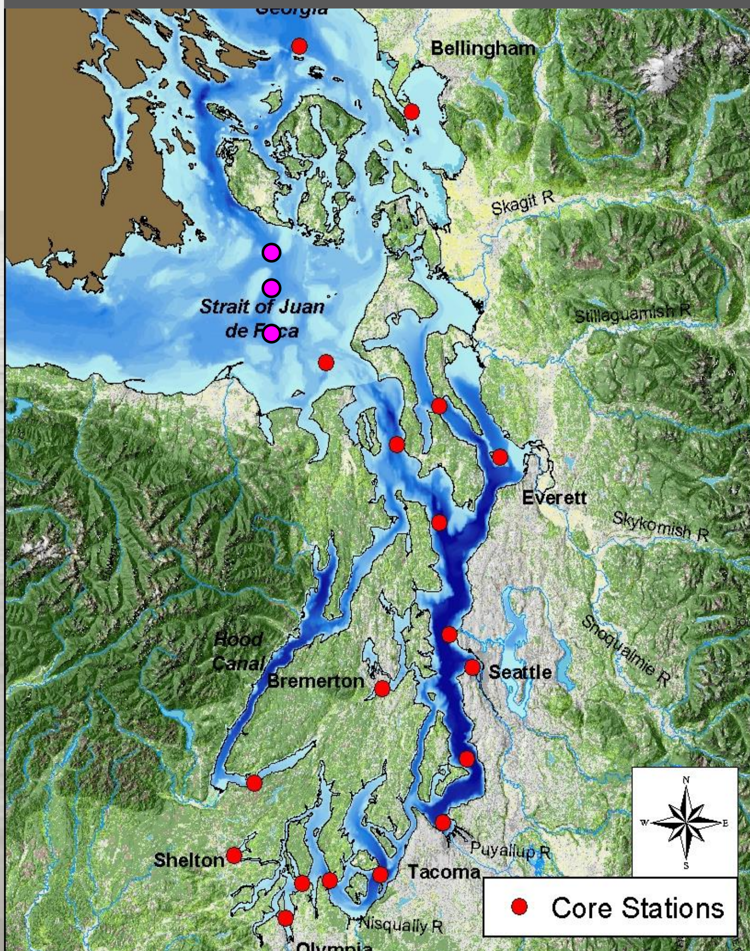






Measuring long-term trends in eutrophication, dissolved oxygen and physical variables

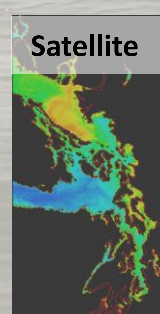
Greater Puget Sound region

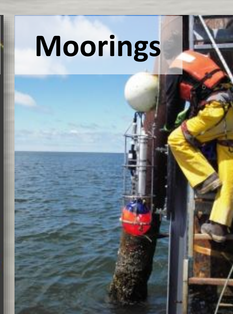


Water Quality variables measured monthly at 27 stations


Seaplane


Ferry


Satellite


Moorings

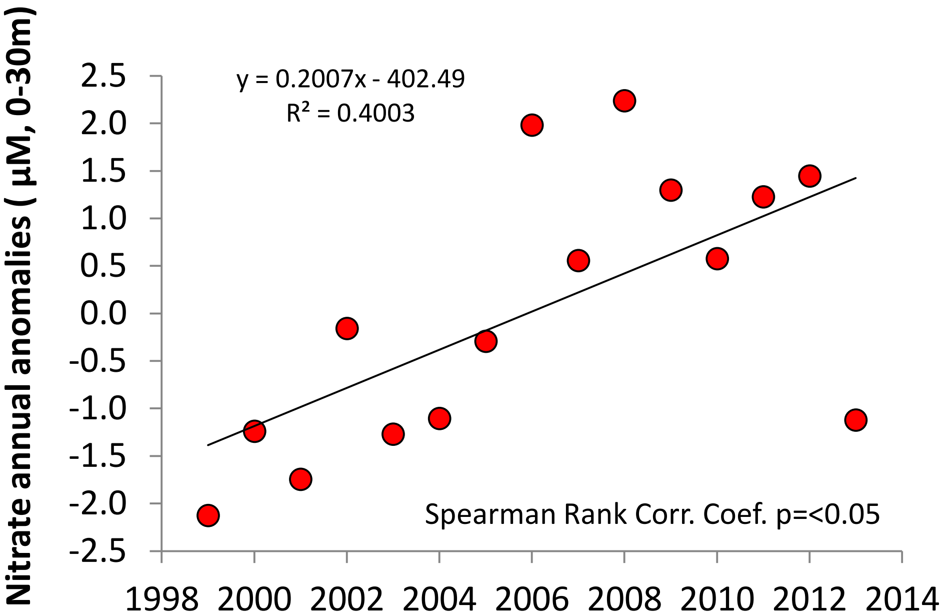
Physical variables
- Temperature
- Salinity
- Density

Chemical variables
- Oxygen
- Nitrate
- Silicate
- Phosphate
- Ammonium
- Nutrient ratios
- pH

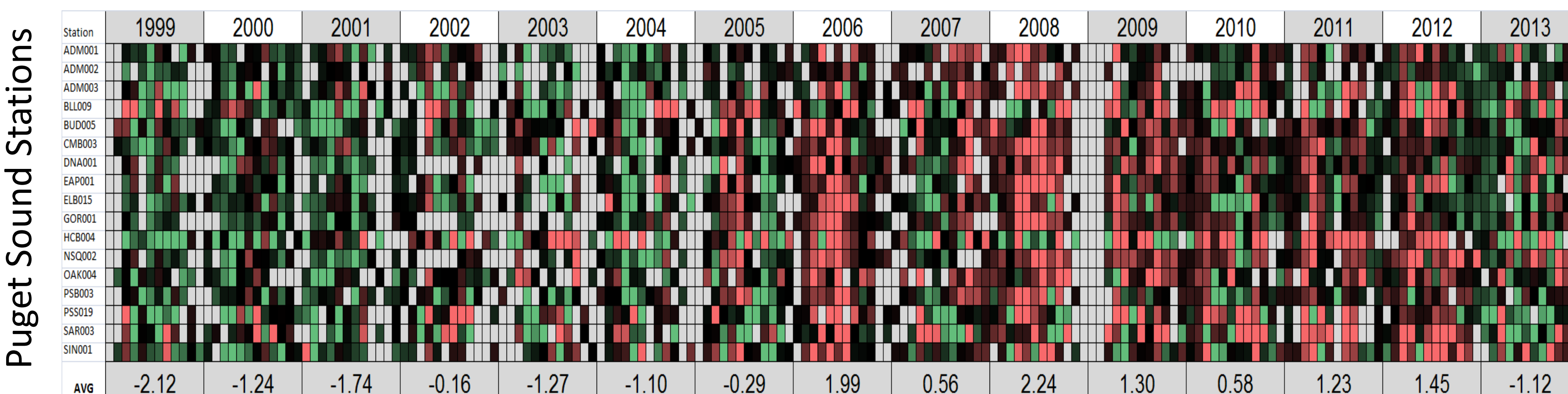
Bio-optical variables
- Water clarity
- Chlorophyll a
- Euphotic depth

Monthly Baselines 1999-2008

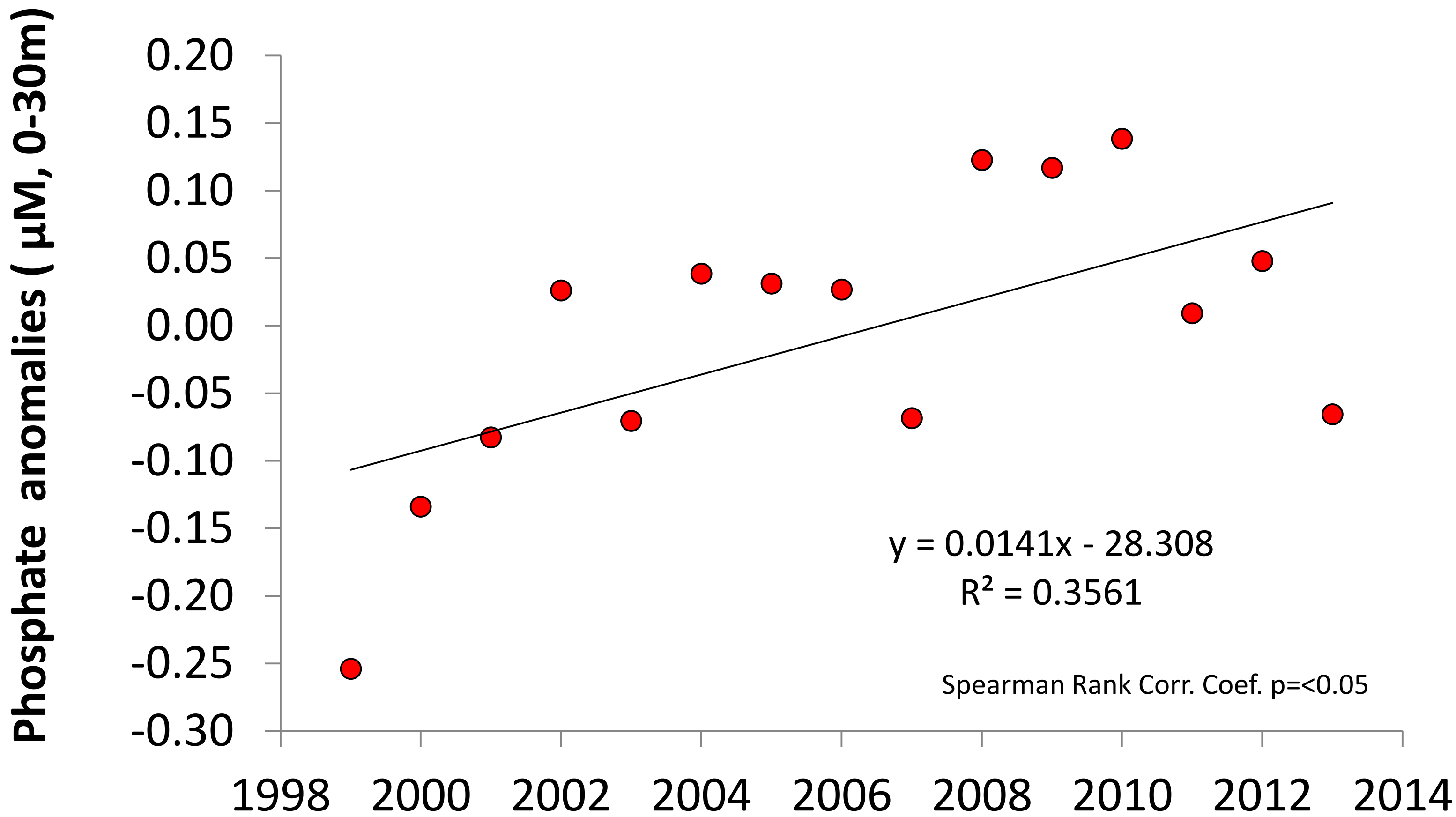
Nitrate concentrations are increasing (non-oceanic cause)



Anomalies in nitrate

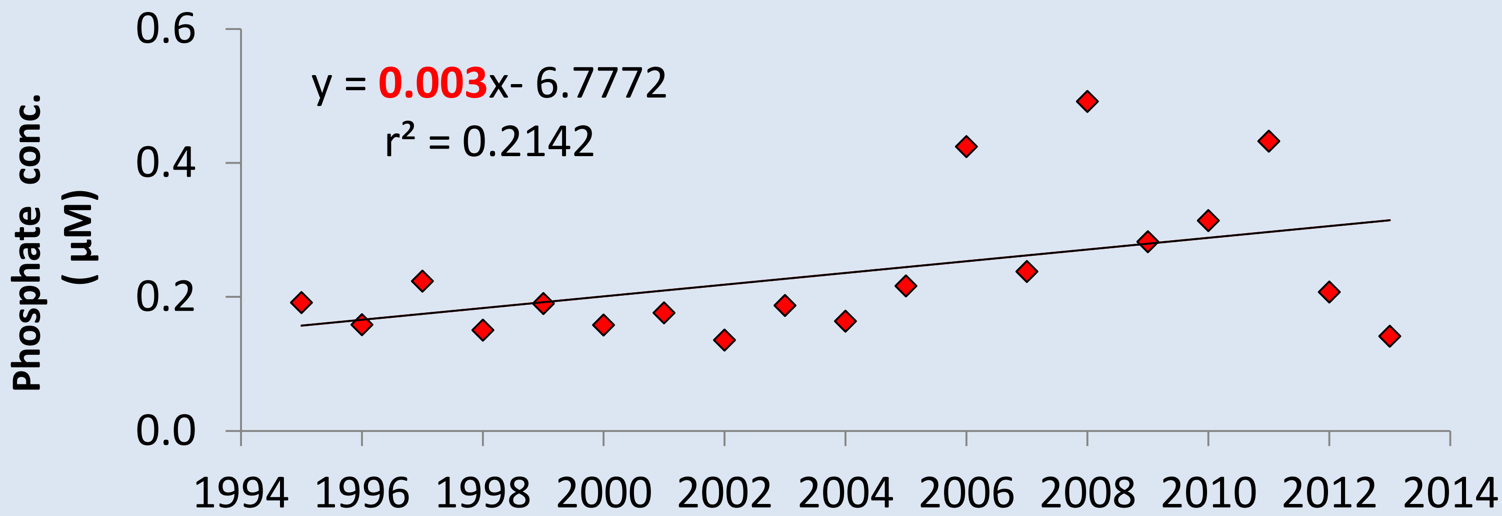


Phosphate concentrations are also increasing

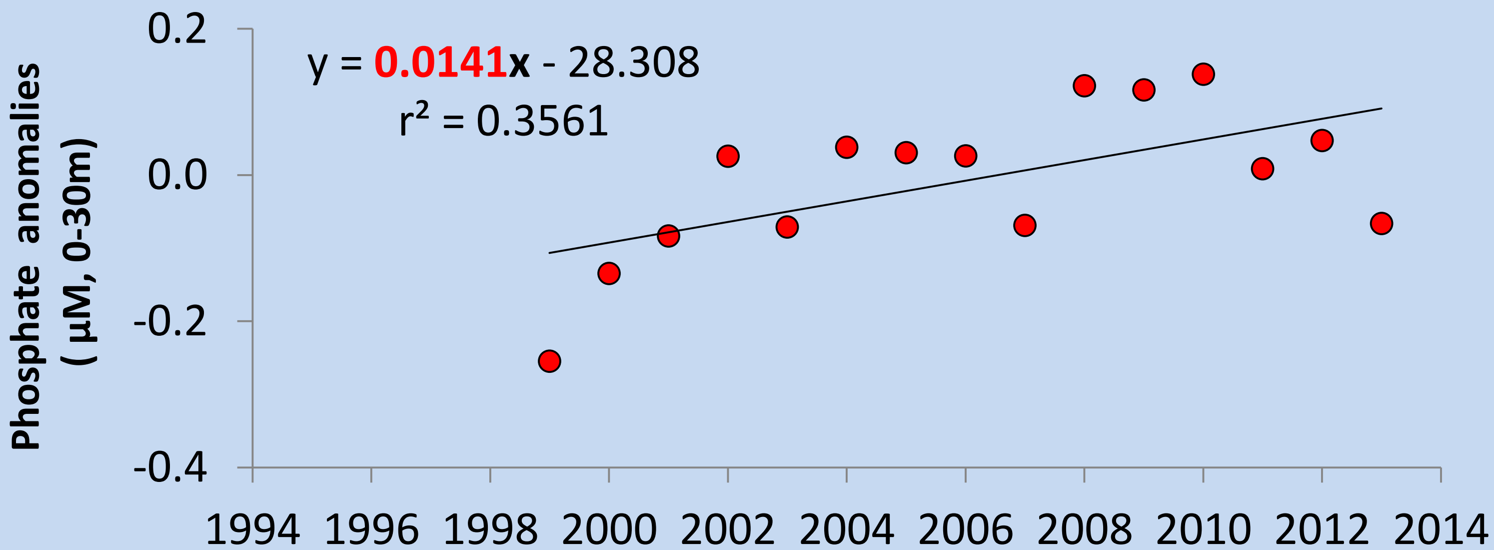


Phosphate long-term trends follow same patterns across the freshwater-saltwater continuum (magnitude difference)

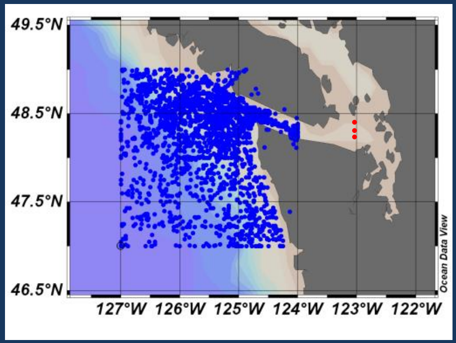
Rivers

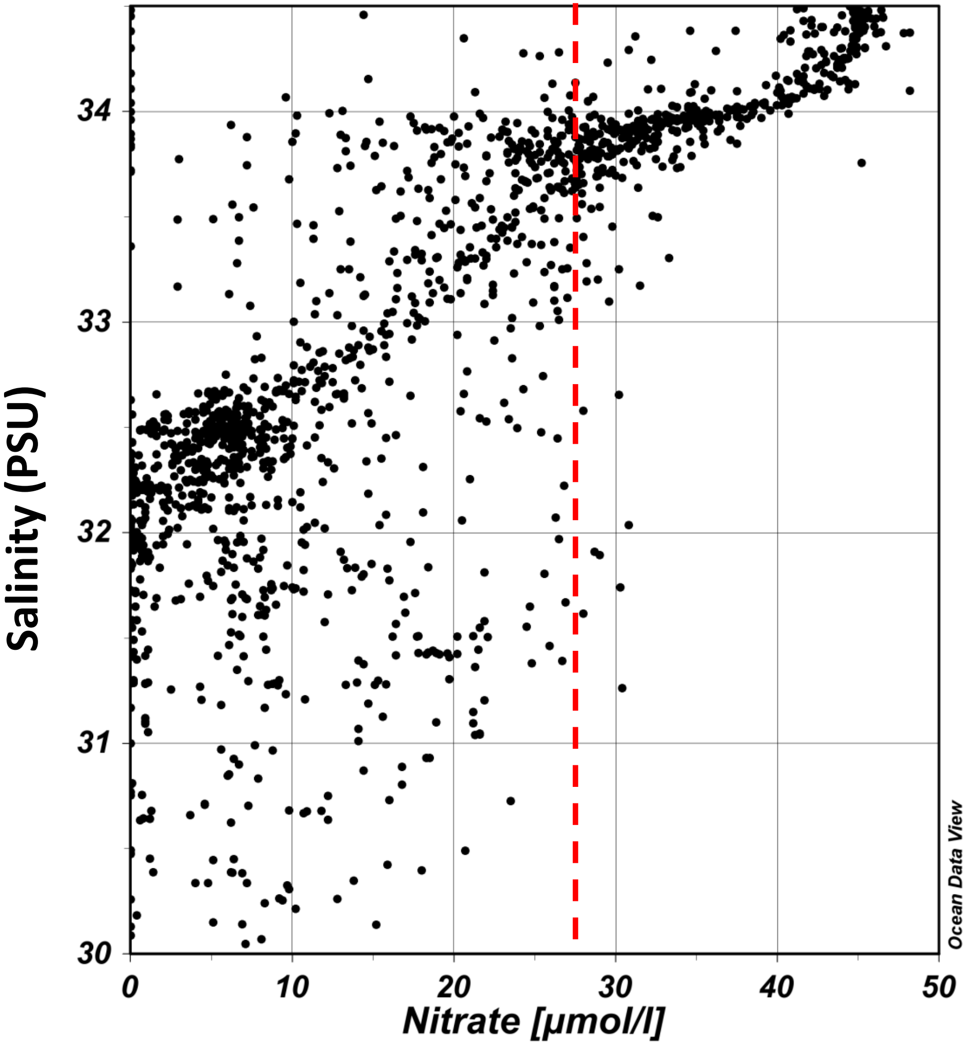


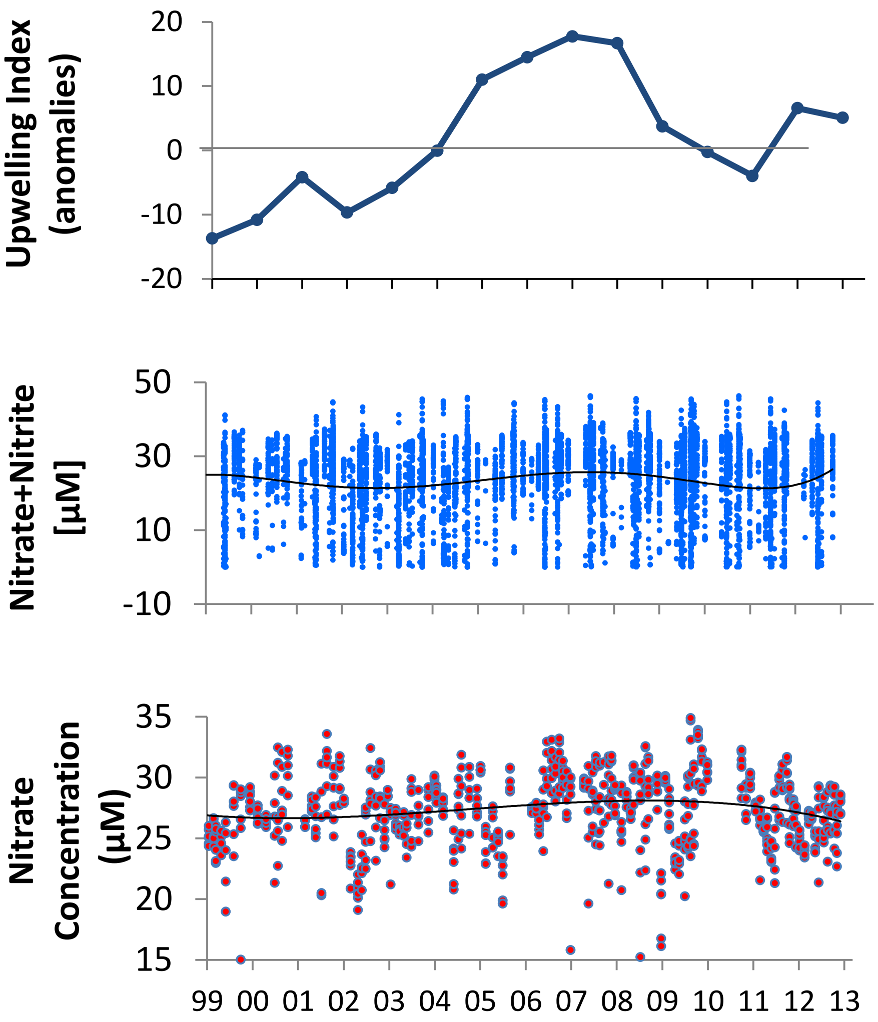
Marine



Ocean water cannot explain the increase in nitrate in Puget Sound *(NODC and DFO)*







Dilemma: Unaccounted Sources?

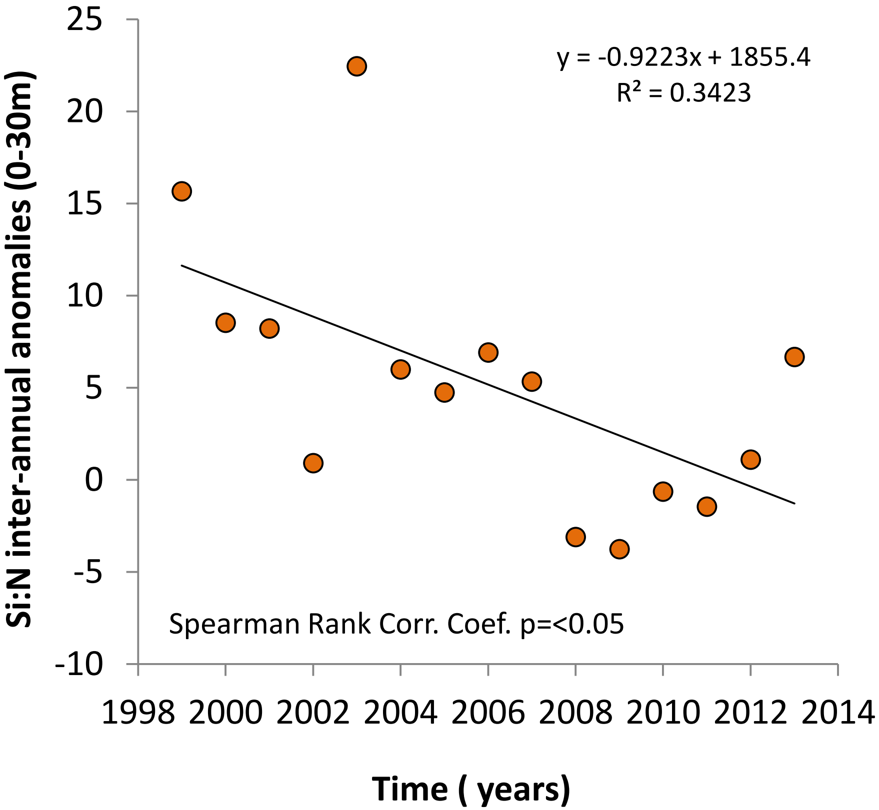
Sources:

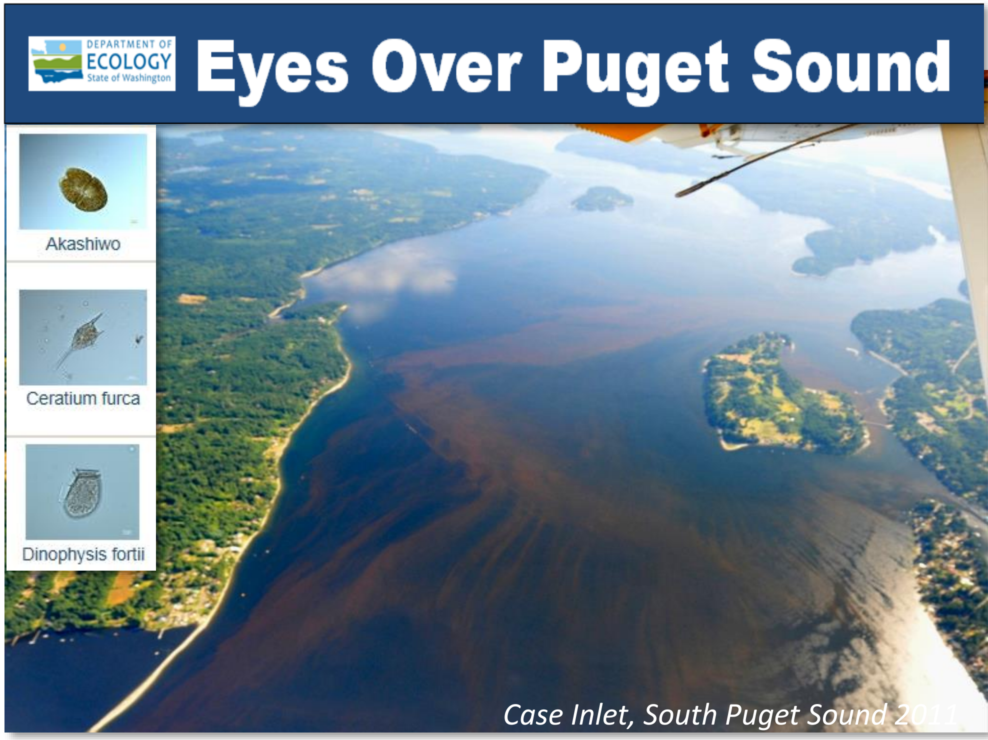
- Nitrogen loading from rivers are relatively unchanged
  - Hallock, D., 2008. River and Stream Water Quality Monitoring Report, Water Year 2008.
    Washington State Department of Ecology, Olympia, WA.
  - Von Prause, M., 2014. River and Stream Water Quality Monitoring Report, Water Year 2013.
    Washington State Department of Ecology, Olympia, WA.
- Nitrogen loading from sewage treatment plants, unchanged.
  - Mohamedali, T., M. Roberts, B. Sackmann, and A. Kolosseus. 2011. Puget Sound Dissolved Oxygen Model Nutrient Load Summary for 1999-2008.
    Washington State Department of Ecology, Olympia, Washington.
- Nitrogen trends in the ocean a possibility but not visible in direct source water to Puget Sound

What are we missing?

Si:N nutrient ratio is falling (eutrophication indicator)

Lower Si:N ratios can favor non-silicified phytoplankton taxa	Large and abundant flagellate blooms at the water surface





http://green2.kingcounty.gov/marine/Photo/Type/2

Ocean not a driver:

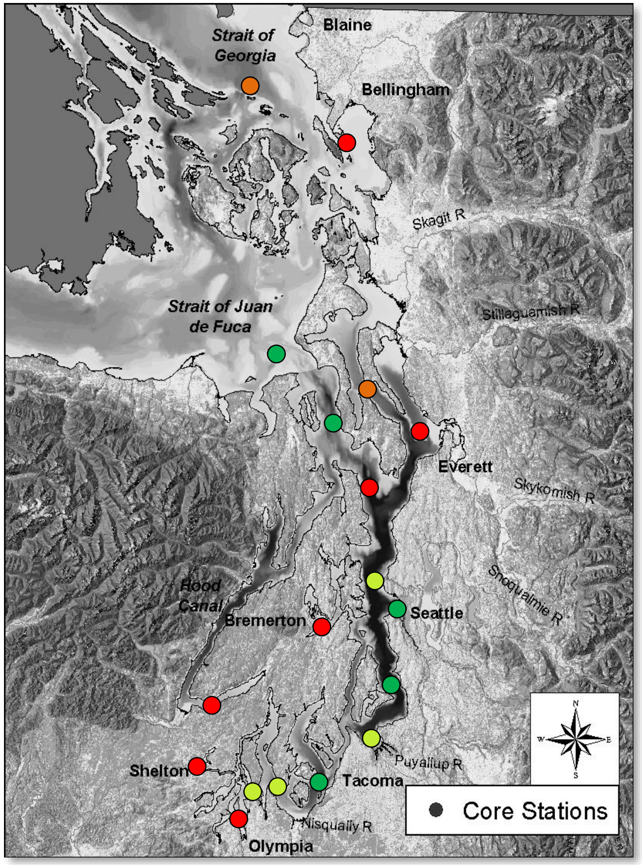
Variability in ocean Si:N two orders of magnitude lower, no trend.

Si:N ratio trends in Puget Sound

A shift in the Si:N atomic ratio <1:1 increases the proportion of flagellate algae, (Officer and Ryther, 1980).

Independent of the ocean, the Si:N ratios continue to fall!

In some places the projected 1:1 ratio is already reached!



Month	Delta 14-y	Years to 1:1
ADM002	-0.2	56
ADM001	-0.2	83
PSB003	-0.6	24
GRG002	-1.0	12
EAP001	-0.4	39
GOR001	-0.4	43
ADM003	-3.0	5
ELB015	-0.4	43
CMB003	-0.7	25
NSQ002	-0.5	37
DNA001	-0.8	24
SIN001	-8.4	2
PSS019	-7.2	2
SAR003	-3.3	6
BLL009	-7.3	2
OAK004	-120.6	0
HCB004	-43.4	1
BUD005	-37.9	1

Tipping point is reached in many places!

Aerial photography 7-28-2014

Red-brown bloom mixed into sediment-rich river plume. Jellyfish patches.
Location: Deepwater Point, Totten Inlet (South Sound), 10:27 AM.

Observed long-term patterns in PS

- Nutrients are increasing in Puget Sound surface water and the nutrient balance is changing.

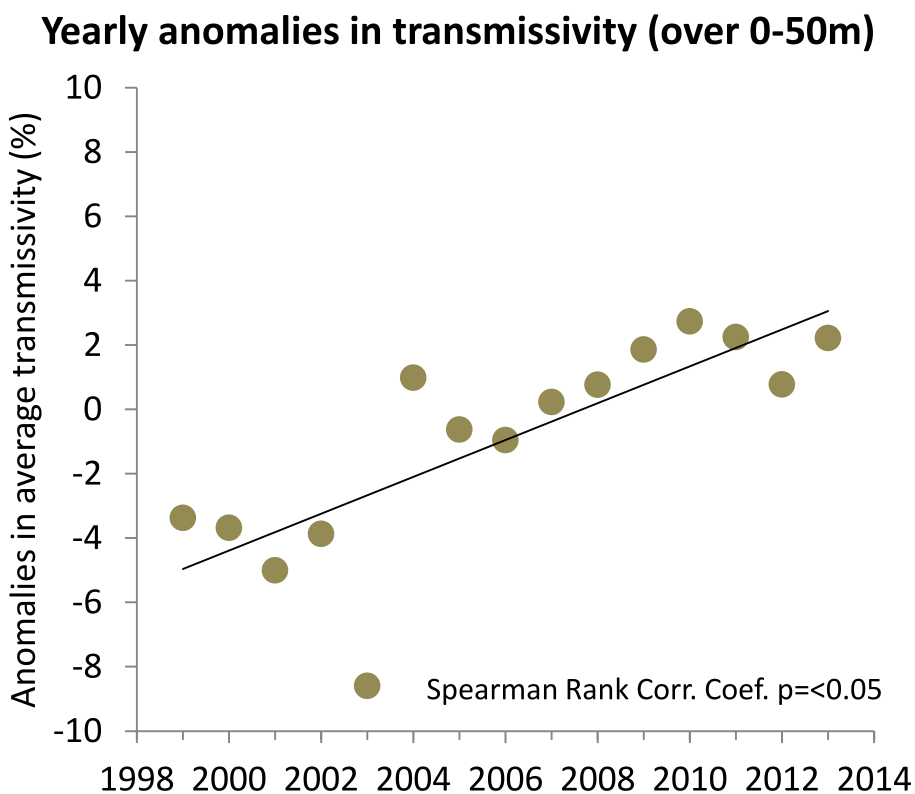
- Dinoflagellate blooms at surface are abundant, frequent and of large scale and ubiquitous.

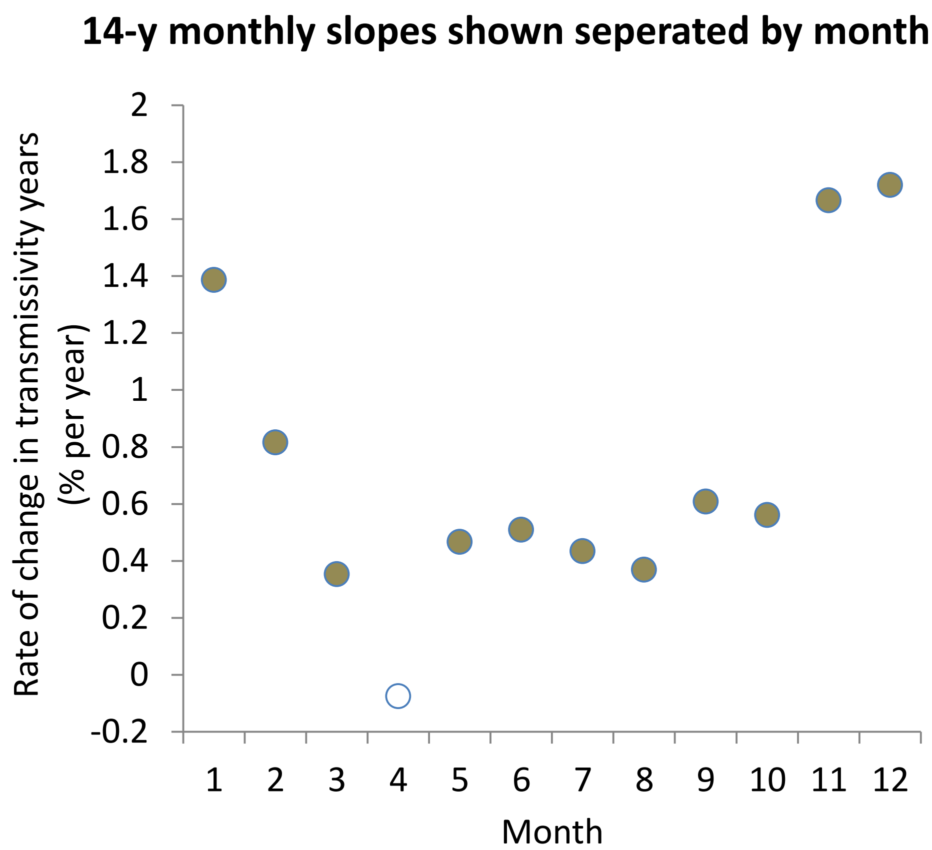
- Water below is, however, getting clearer

- Subsurface phytoplankton biomass is decreasing!

- Vertical shift in phytoplankton biomass (changing seasonal patterns).

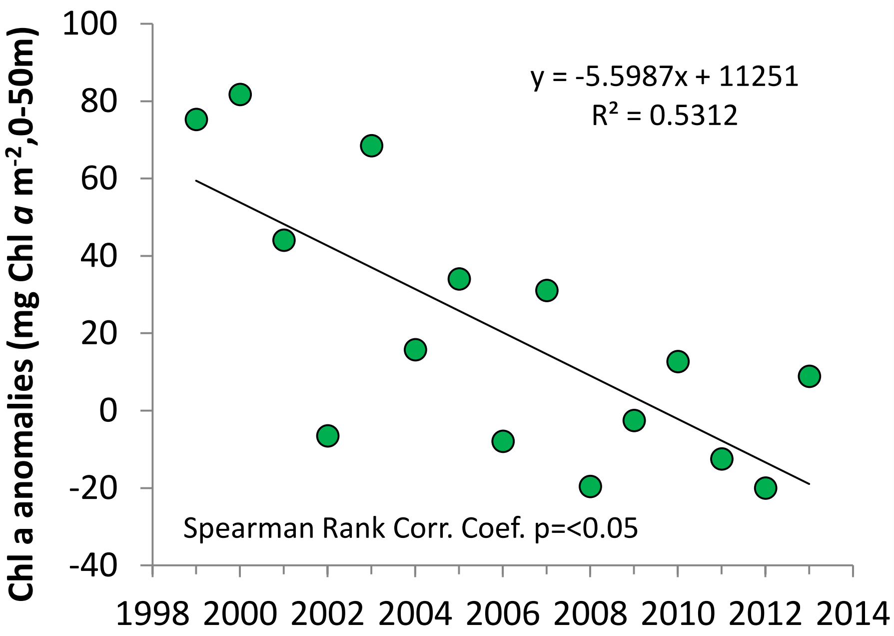
Puget Sound water is getting clearer



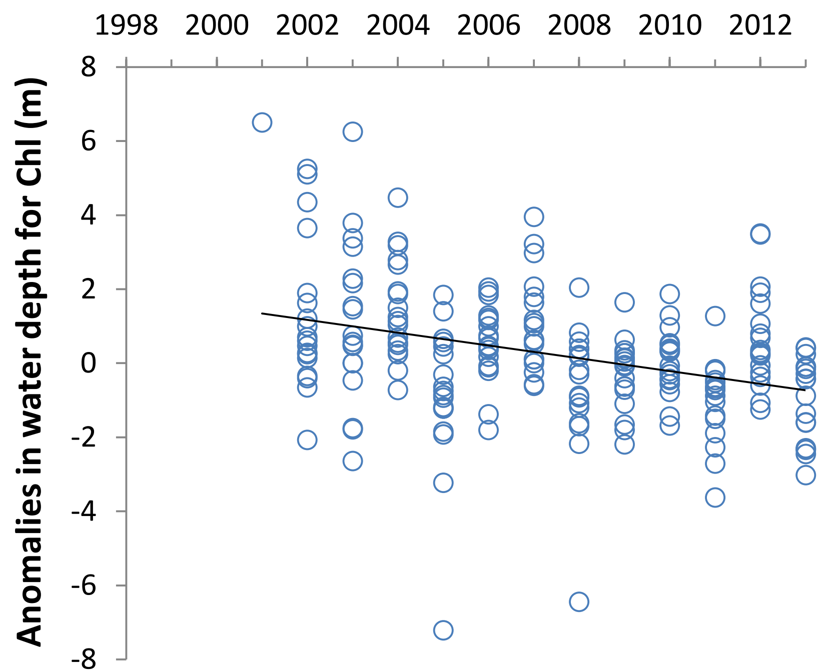


Phytoplankton biomass: a 14-year decline (0-50m) and a shift to deeper water

Depth integrated Chl a biomass



Depth of 50% depth integrated Chl a biomass



2-3m deeper phytoplankton layer

Why is nitrogen going up?

Why are nutrient ratios changing?

To what is the system responding?

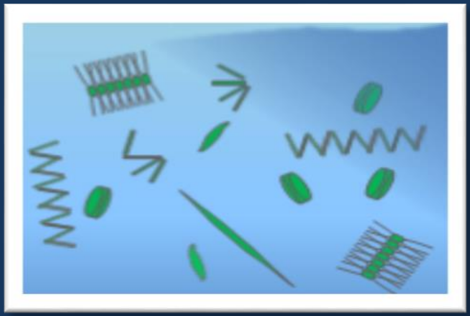
Do we need to look at the food web?

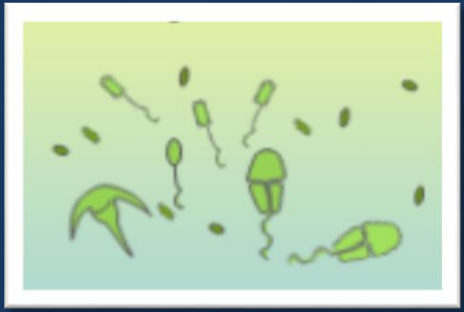
--- It is not stratification ---

Nutrient balance does affect species composition

Diatoms sink fast!

Aggregates





Qualitative difference (food and sinking) (energy and material cycling)

Diatom dominated: ***Good food for grazers***

1. Silicate stems from land weathering.
2. Frustules slow remineralization fast sinking.

Flagellate dominated: ***Poor food for grazers***

1. Motility allows positioning in the water.
2. Need only nitrogen and phosphorus.

Temporal shift:

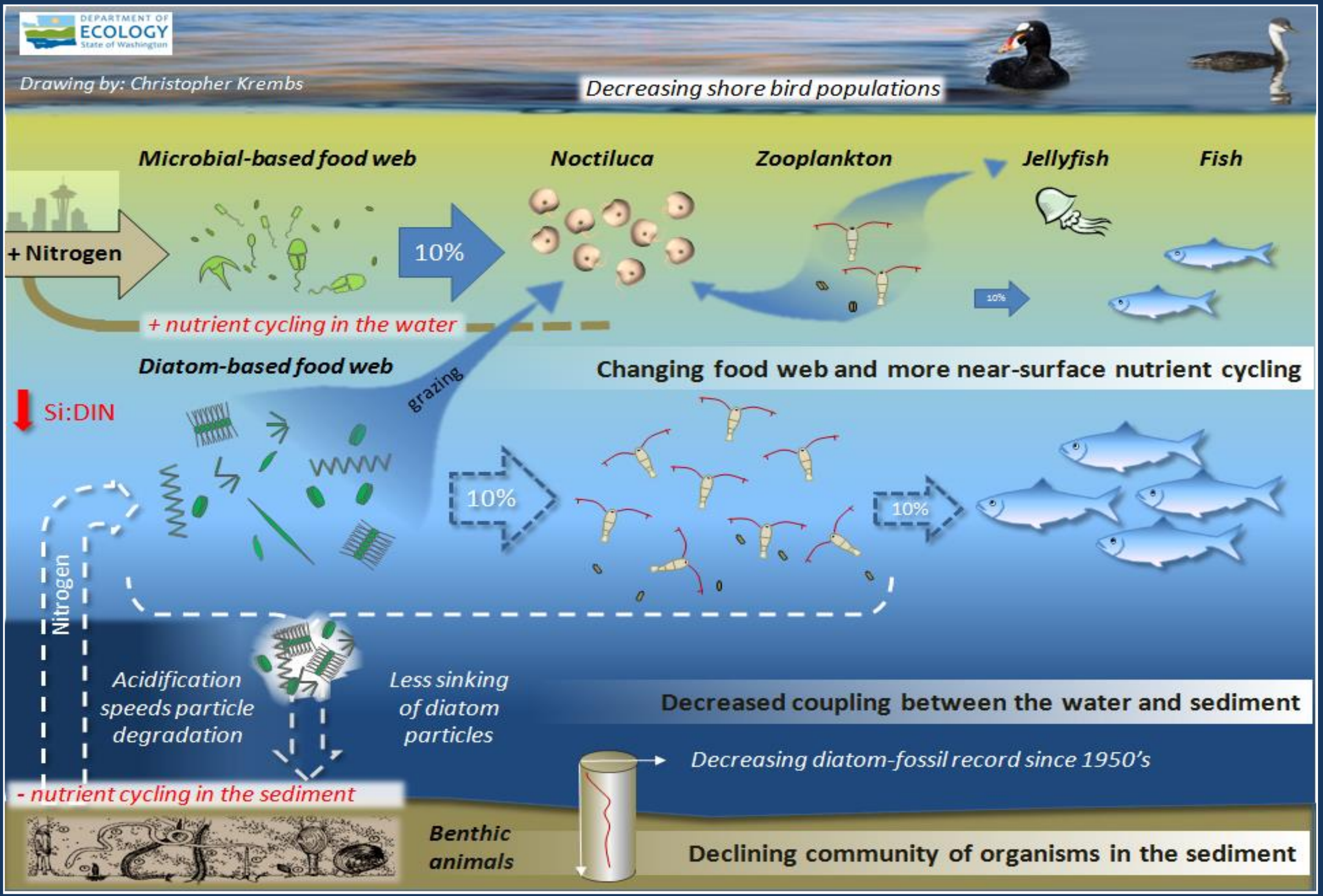
Late spring diatom dominated blooms.

Late summer flagellate dominated blooms.

Spatial shift:

Sewage effluent and eutrophication promote flagellate dominated population.

Hypothesis for combining a series of recent observations affecting energy and material transfer to higher trophic levels



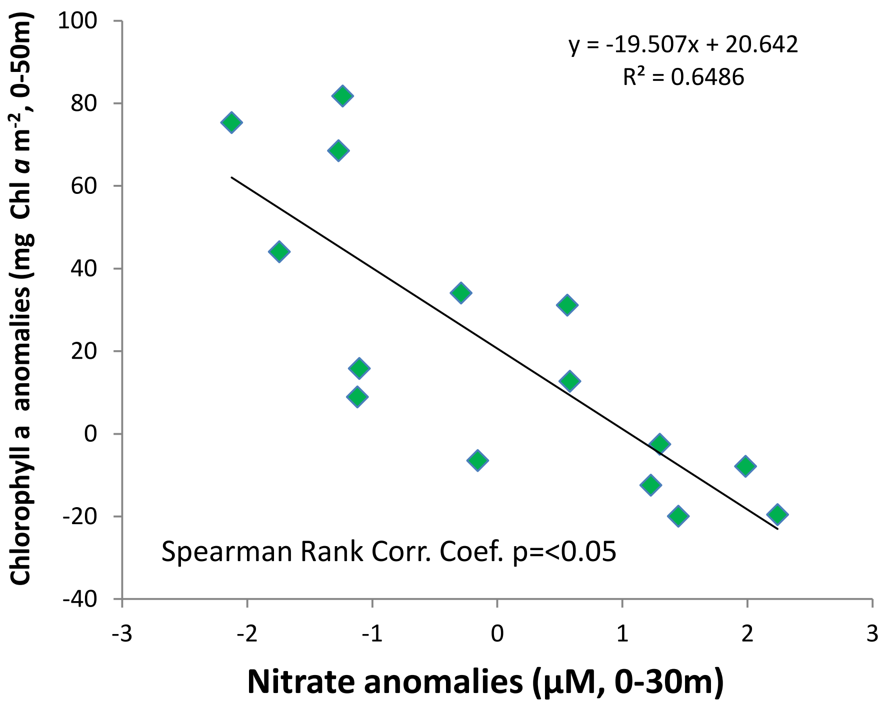
Increases in nitrate conc. could be caused by a top-down control on phytoplankton biomass.

Noctiluca **a visible harbinger of a food web change?**

Are changes in higher tropic levels part of a story of the low food web?

Inter-annual variability in phytoplankton biomass could explain changes in macro-nutrients?

Nitrate and Chl *a*



Micro-zooplankton (<200 µm)

Micro-zooplankton grazers can remove the entire diatom standing stock <u>each day</u>!

Balance between microzooplankton grazing and phytoplankton growth in Dabob Bay (Hood Canal)…

Leising et al., 2005. The balance between microzooplankton grazing and phytoplankton growth in a highly productive estuarine fjord. Progress in Oceanography 67:366–383.

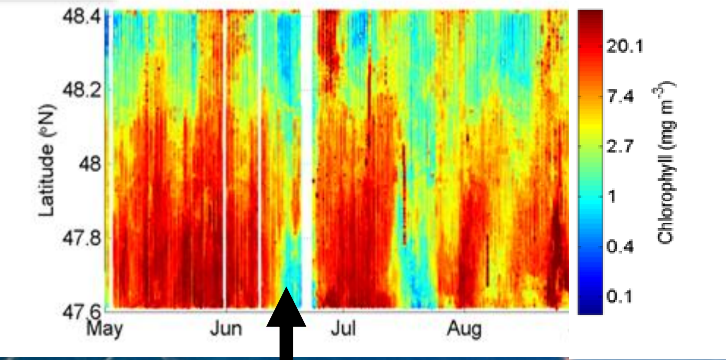
What controls phytoplankton inter-annual variability could also control nutrients in Puget Sound?

Noctiluca blooms are large (eutrophication indicator)

A strong competitor to copepods that feed on diatoms!

Food : <u>No food preference!</u> (*Diatoms, flagellates, detritus, nauplii, copepod and fish eggs…)*

Chlorophyll a (in situ fluorescence)



Noctiluca rapidly recycles sinking fecal pellets and retains nutrients in the surface.

(Kiørboe, Thomas 2003)

Eyes Over Puget Sound

Up-to-date observations of visible water quality conditions in Puget Sound and the Strait of Juan de Fuca

Summary

- The marine food web shows symptoms of eutrophied coastal environments (*Noctiluca , flagellates, jellyfish*)
- Growth limiting nutrients in freshwater & marine water increase (rivers: P, marine N and P). Only phosphate in rivers matches the marine phosphate pattern, not magnitude.
- Changing marine nutrient ratios could have affected the base of the food web and how nitrogen is processed. In marine water the turning point for species shift is approaching in many places.
- Long-term marine trends suggest changing biogeochemical processes (summer/fall around the seasonal DO min).

What next?

Determine the causes behind changing nutrient ratios and changes in the lower marine food web.

1. Unaccounted nutrient inputs from land and rivers?

2. What drives the changes in the food web (nutrient quality)

3. Quantitatively test assumptions about the nitrogen cycle and the effect of ocean acidification.

River & Stream Monitoring Unit (NW & SW Regions)




Brad Hopkins, Markus Von Prause, Bill Ward, Howard Christensen, Casey Clishe

DEPARTMENT OF ECOLOGY State of Washington

Washington State Department of Ecology

PSEMP

Long-Term Marine Monitoring Unit (Marine Waters)



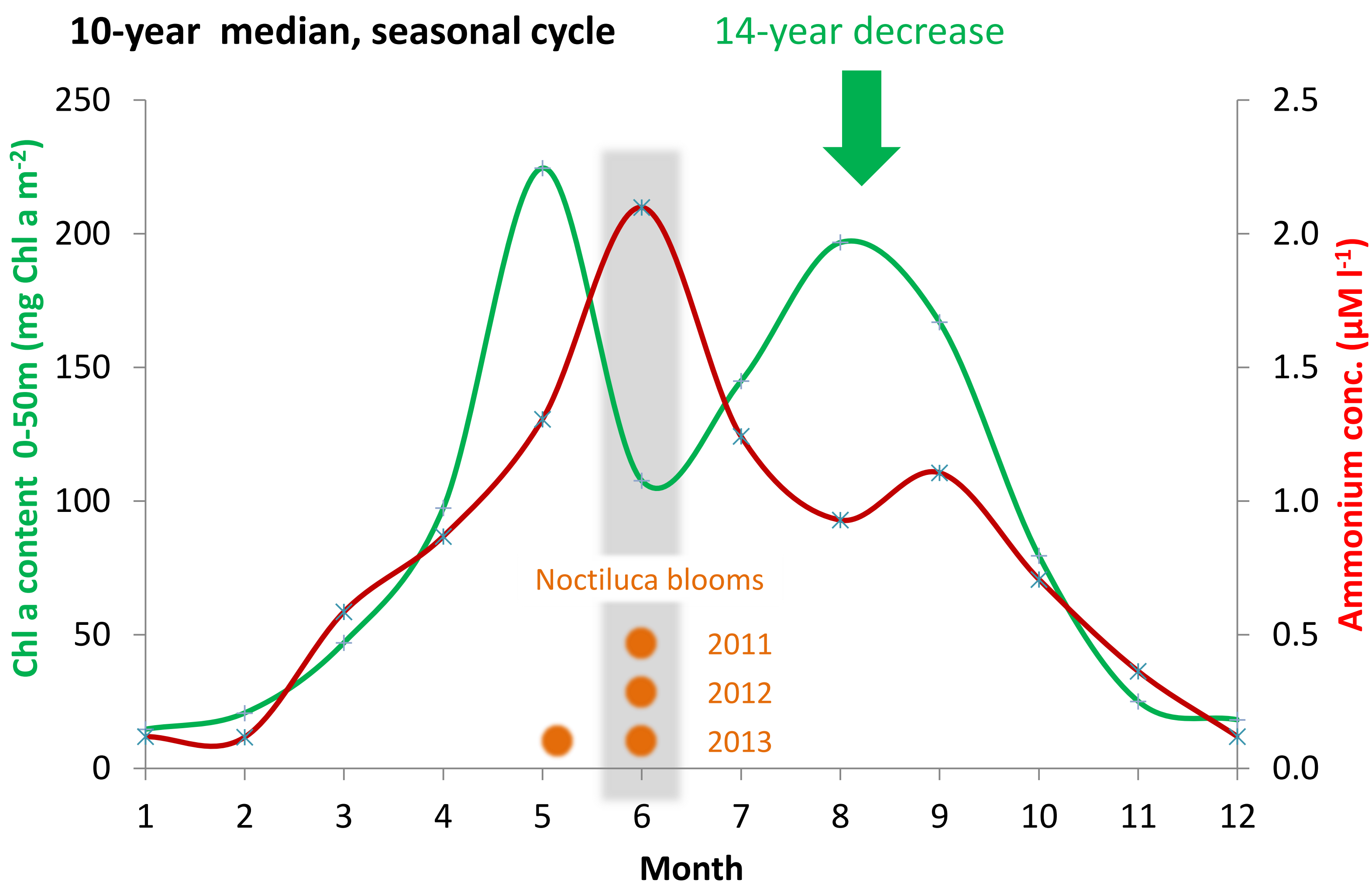




Carol Maloy, C. Krembs, J. Bos, S. Albertson, B. Sackmann, M. Keyzers, L. Friedenberg, J. Ruffner

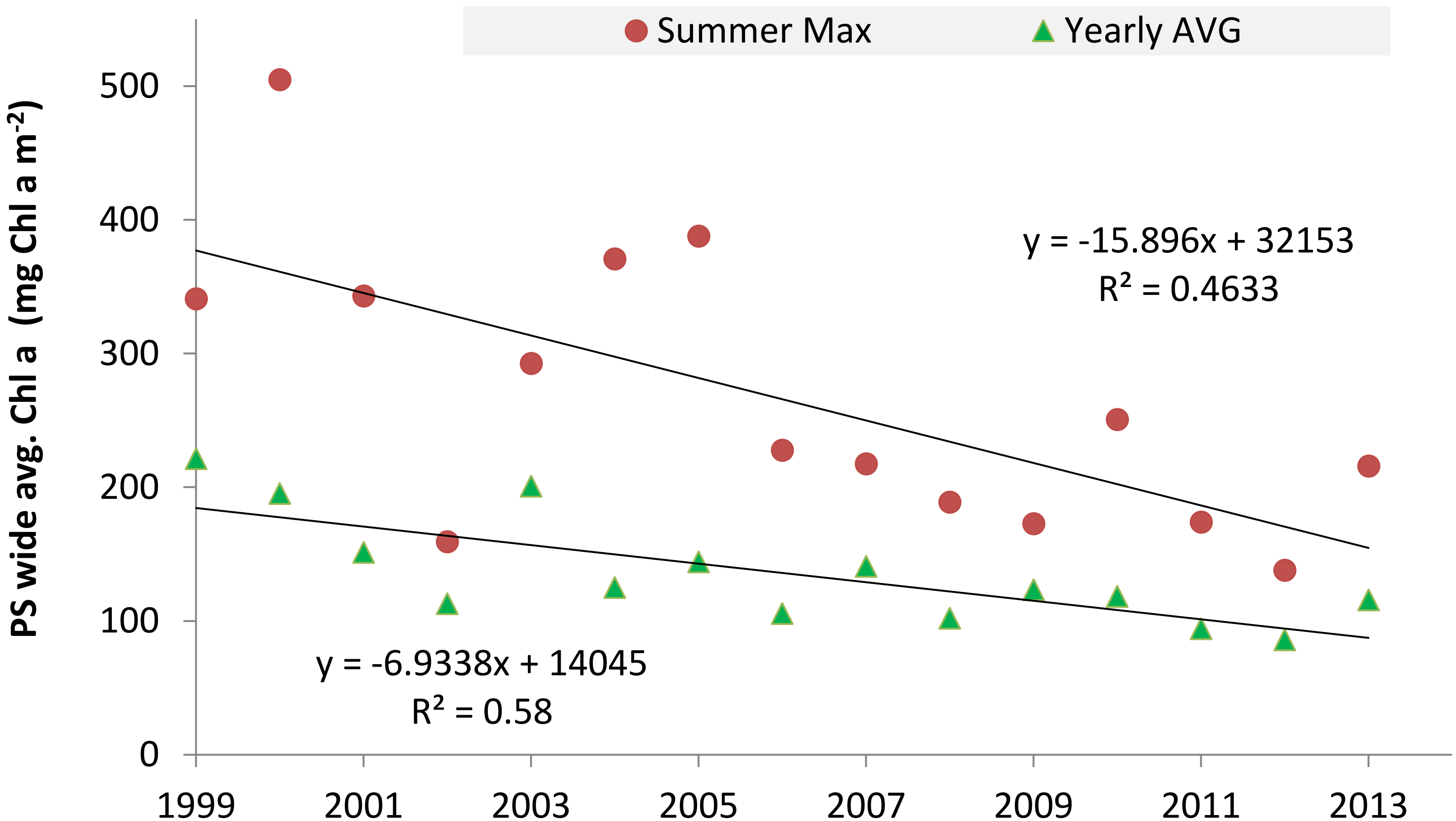
FOR DISCUSSION

Grazing is reflected in the seasonality of Phytoplankton biomass and NH_4 in Puget Sound

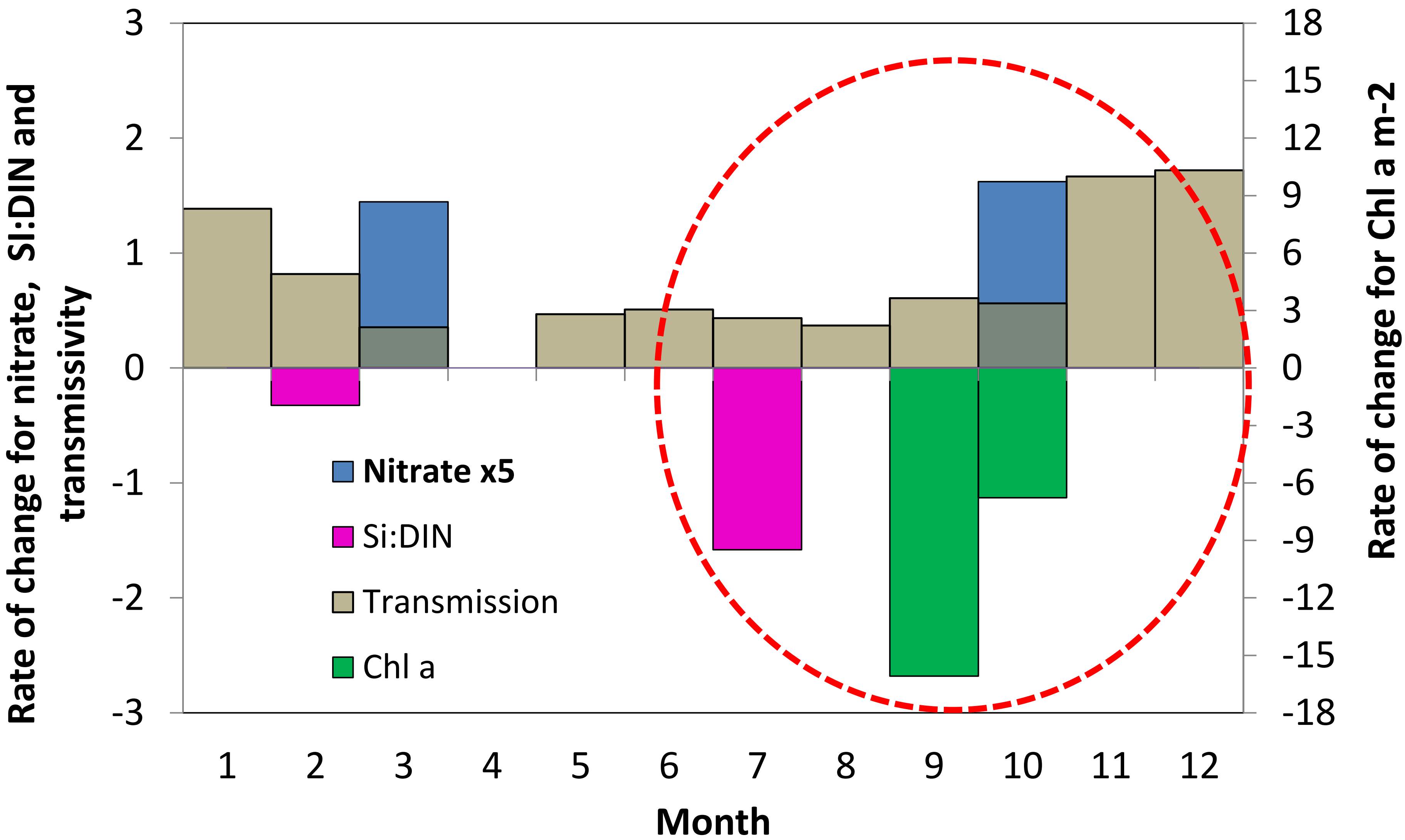


Chl a summer peak looses its strength

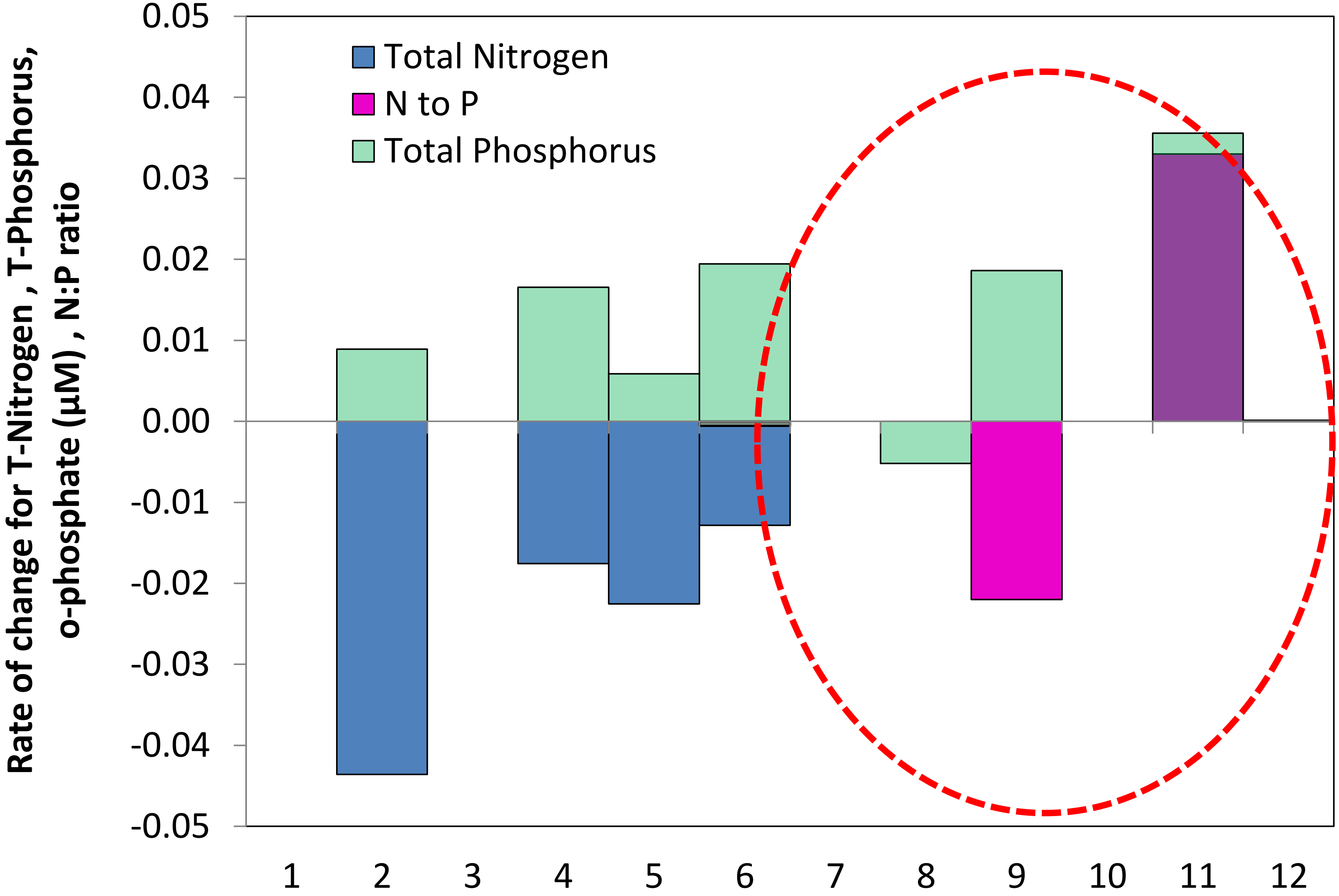
Note: NH_4 max also decreases in late summer; average is unchanged



Summary of significant **marine** long-term trends seperated by month



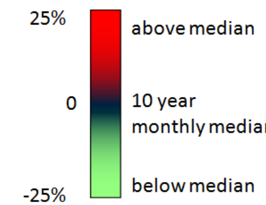
Summary of significant **freshwater** long-term trends separated by month



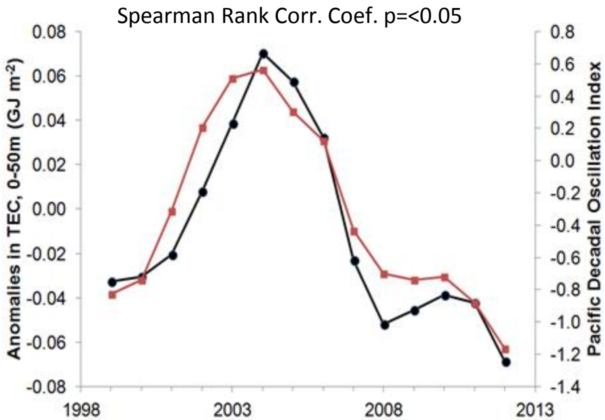
Ocean boundary conditions impact PS water quality

A-B **Sea Surface Temperature -** Pacific Decadal Oscillations Index

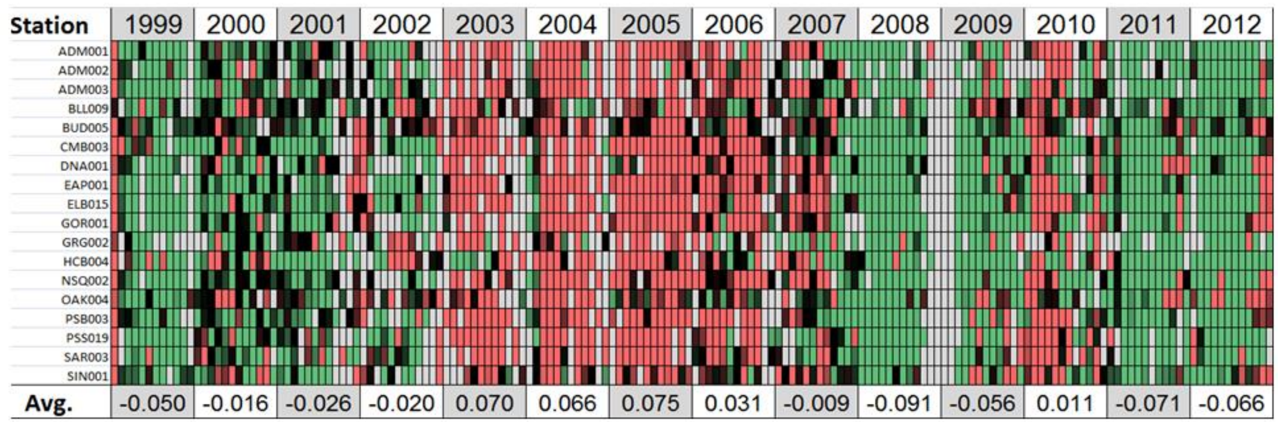
C-D **Upwelling -** Upwelling Index (anomalies)



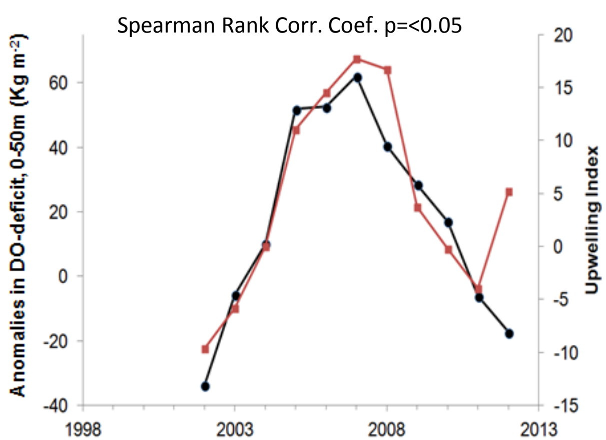
A. Pacific Decadal Oscillation Index



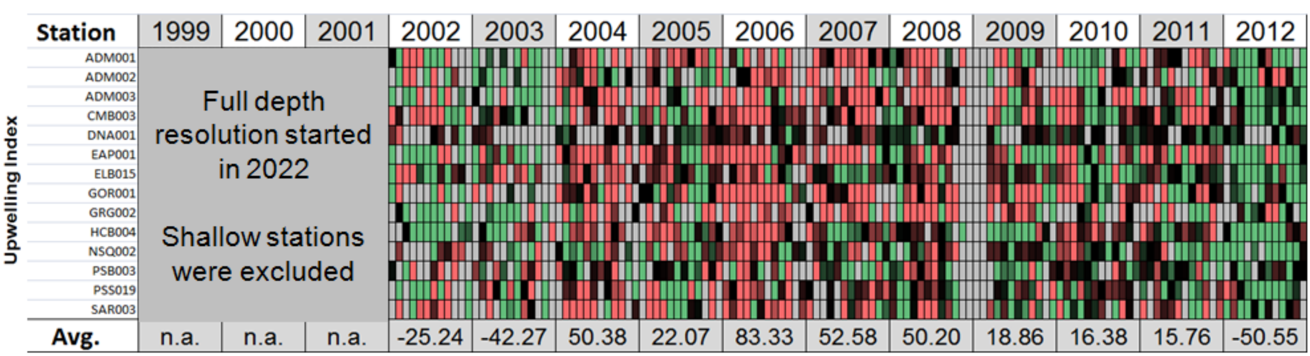
B. *Anomalies in Thermal Energy Content, 0-50m*



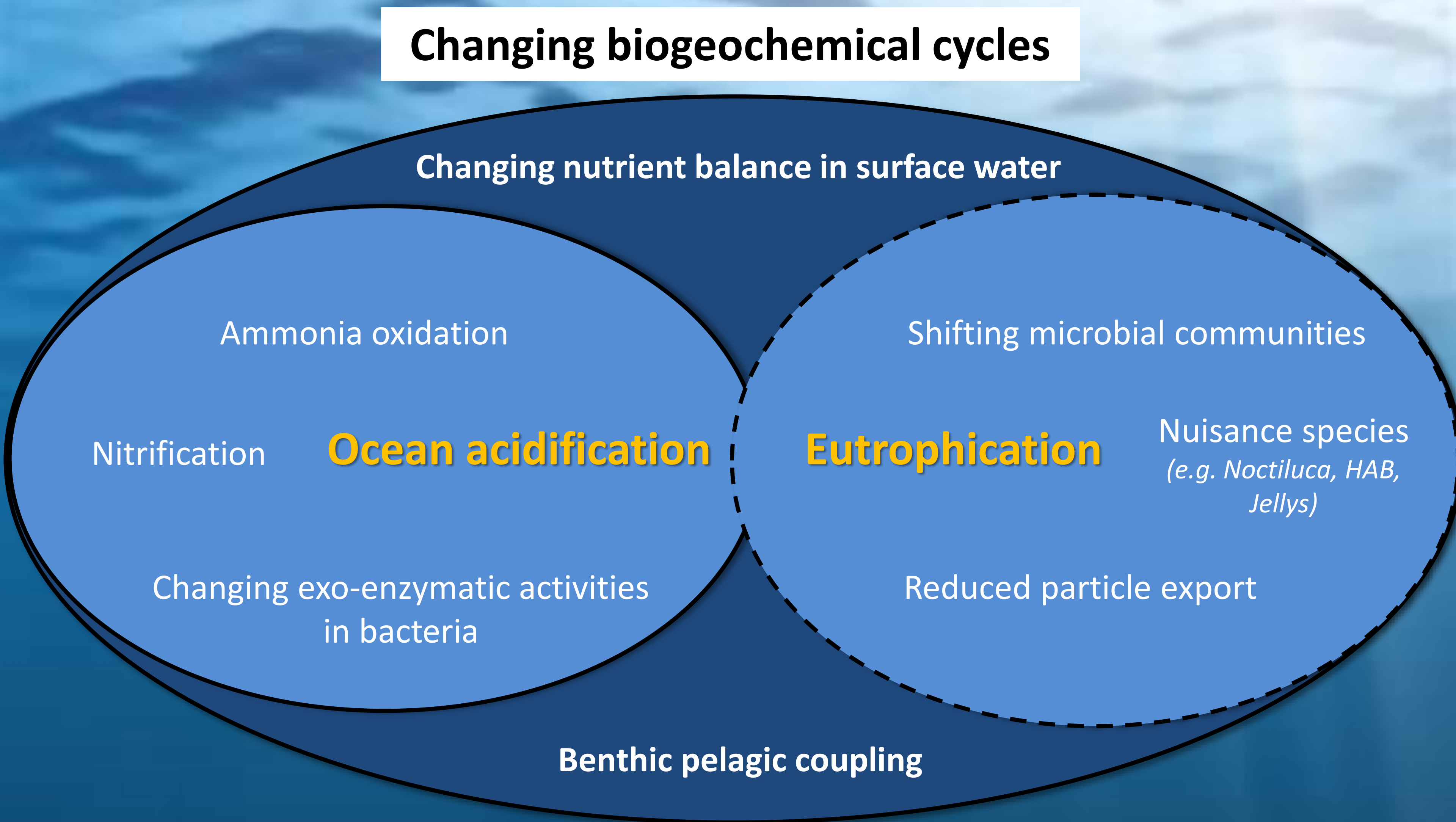
C. Upwelling Index (NOAA)



D. *Anomalies in Dissolved Oxygen Deficit, 0-50m*



Dilemma: Unaccounted Processes?



Long-term increases in Great Lakes mediated by **changes in nitrification** (NH4 -> NO3)

Limnol. Oceanogr., 58(1), 2013, 276–286

doi:10.4319/lo.2013.58.1.0276

Rates and controls of nitrification in a large oligotrophic lake

Gaston E. Small,[a,1,*] George S. Bullerjahn,[b] Robert W. Sterner,[a] Benjamin F. N. Beall,[b] Sandra Brovold,[a] Jacques C. Finlay,[a] Robert M. L. McKay,[b] and Maitreyee Mukherjee[b]

[a] Department of Ecology, Evolution, and Behavior, University of Minnesota, St. Paul, Minnesota
[b] Department of Biological Sciences, Bowling Green State University, Bowling Green, Ohio

Abstract

Recent discoveries have altered prevailing paradigms concerning the conditions under which nitrification takes place and the organisms responsible for nitrification in aquatic ecosystems. In Lake Superior, nitrate (NO_3^-) concentrations have increased fivefold in the past century. Although previous evidence indicated that most NO_3^- is generated by nitrification within the lake, important questions remain concerning the magnitude and controls of nitrification, and which microbial groups are primarily responsible for this process. We measured water-column

Recent studies in marine environments have shown that nitrification can occur in the euphotic zone (Fernandez and Raimbault 2007; Clark et al. 2008), challenging the fundamental assumption of the classic "new production" paradigm (Dugdale and Goering 1967). The recent discovery that Archaea are the most abundant ammonia oxidizers in the ocean (Könneke et al. 2005) highlights how little is understood about the ecological controls underpinning nitrification.

Vol. 492: 1–8, 2013
doi: 10.3354/meps10526

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published October 31

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FEATURE ARTICLE

Acidification alters the composition of ammonia-oxidizing microbial assemblages in marine mesocosms

Jennifer L. Bowen[1,*], Patrick J. Kearns[1], Michael Holcomb[2,4], Bess B. Ward[3]

... Ammonia oxidation, (first step in nitrification) is pH sensitive

Beman et al. 2011. Global ***declines in oceanic nitrification rates*** *as a consequence of ocean acidification.* ***Proceedings of the National Academy of Sciences (PNAS).*** *vol. 108 no. 1, 208-213.*

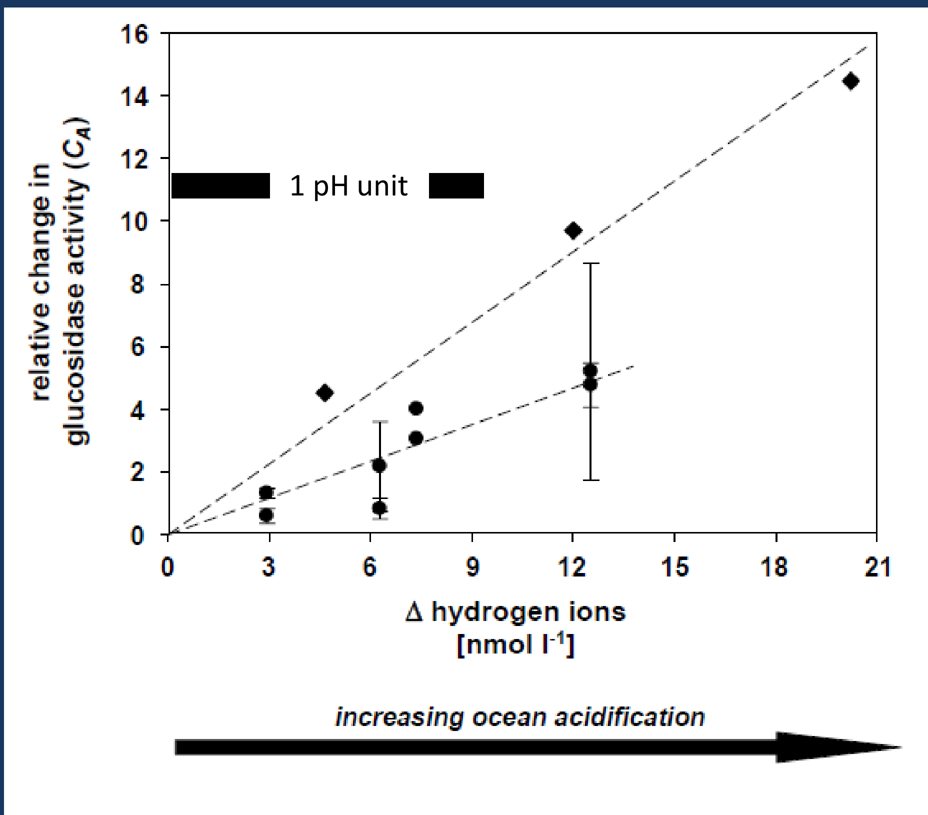
…Increasing acidity in the sea's waters may fundamentally change how <u>nitrogen is cycled</u> in them. -

Acidification increases microbial polysaccharide degradation in the ocean

J. Piontek[1], M. Lunau[1,2], N. Händel[1], C. Borchard[1], M. Wurst[1], and A. Engel[1]

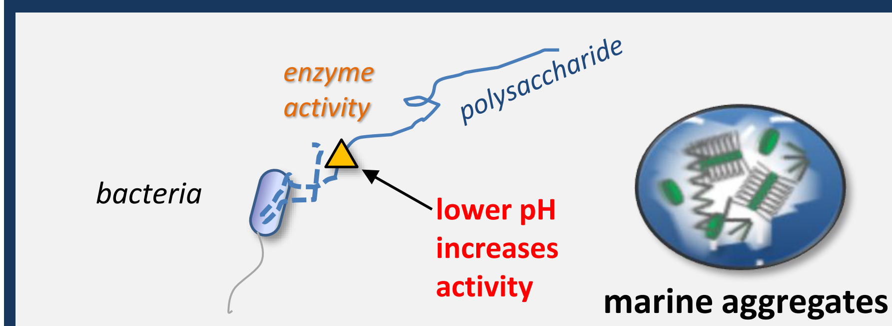
Biogeosciences, 7, 1615–1624, 2010

Are vertical particle flux, and ocean acidification linked?



…degradation of polysaccharides by bacterial **extracellular enzymes was significantly accelerated** during experimental simulation of ocean acidification.

….faster bacterial turnover of polysaccharides at lowered ocean pH has the potential to reduce carbon export …..



Important Topic

Dongyan Liu et al. 2013

Altered **nutrient supply ratios** from increased nitrogen inputs play an important role in the **shifts in diatom and dinoflagellate** assemblages.

Vol. 475: 1–14, 2013
doi: 10.3354/meps10234

MARINE ECOLOGY PROGRESS SERIES
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Published February 14

OPEN ACCESS

FEATURE ARTICLE

Palaeoecological analysis of phytoplankton regime shifts in response to coastal eutrophication

Dongyan Liu[1,*], Xuhong Shen[1,2], Baoping Di[1], Yajun Shi[1], John K. Keesing[1,3], Yujue Wang[1], Yueqi Wang[1,2]

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ABSTRACT: We used a multiple-proxy palaeoecological method to reconstruct a 100 yr time series showing coastal eutrophic processes and phytoplankton responses. Total organic carbon, total nitrogen, diatom frustules, dinoflagellate cysts, brassicasterol and dinosterol were extracted from chronologic sediment cores in Sishili Bay, a polluted area in China. The cores showed that eutrophication occurred during about 1975 to 1985, which corresponds to increased human activity associated with China's economic development since 1978. During eutrophication, the biomass of diatoms and dinoflagellates increased, and dominant species shifted abruptly. The small, heavily silicified diatoms *Cyclotella stylorum* and *Paralia sulcata* gradually took the place of the large dominant diatom *Coscinodiscus radiatus*, while dinoflagellates displayed a progressive increase since 1975. Compared to changes in temperature and rainfall during 1950 to 2010, increased fertilizer use, marine aquaculture and sewage discharge showed a better match to the increasing trend in biomass, species shift and nutrient concentration. Altered nutrient supply ratios caused by increased nitrogen inputs play an important role in the shifts in diatom and dinoflagellate assemblages.

KEY WORDS: Palaeoecology · Eutrophication · Diatom · Dinoflagellate · Biomarkers

Paleoecological methods make it possible to reconstruct anthropogenic effects such as coastal eutrophication over periods of a century.

Photos: Dongyan Liu & Zhijun Dong

INTRODUCTION

Over recent decades, coastal waters have undergone significant deterioration, much of it due to anthropogenic eutrophication (de Jonge et al. 2002) and climate change (Harley et al. 2006). Setting a target for nutrient reduction requires not only information on nutrient sources, distribution and recycling, but also requires knowledge of the trends and baselines of nutrient concentrations in coastal waters

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Changes in the vertical distribution of primary production in response to land-based nitrogen loading

Maren Moltke Lyngsgaard,[1,2,*] Stiig Markager,[1] and Katherine Richardson [2]

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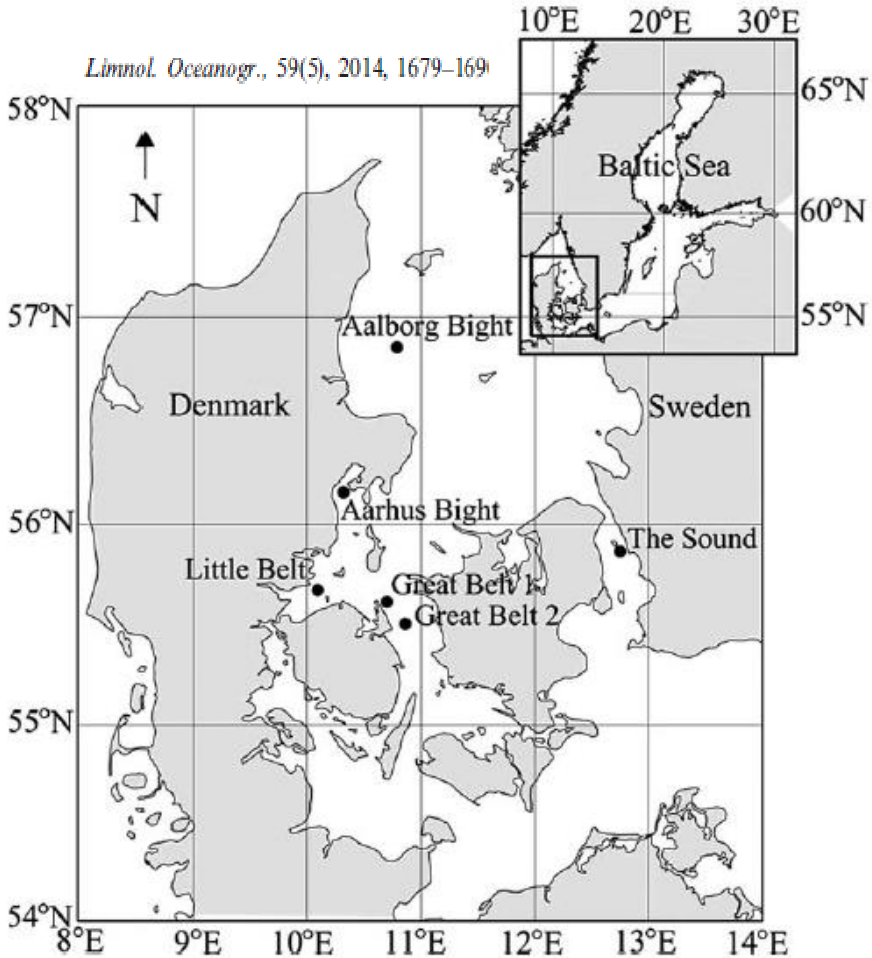

Fig. 1. The Baltic Sea Transition Zone (BSTZ) and location of the six stations.

……vertical distribution of primary production changed <u>as a function of landbased N-loading</u> at Danish coast between 1998 and 2012.

Consistent with observations in Puget Sound?!

Corrobarates that nitrogen increase due to higher loads seems less likely?

Important Topic

Vasas et al. 2007

HAB-forming species and Noctiluca **stimulate the microbial network**, but reduce higher trophic levels (fish).

The loss of planktivorous fishes acts together with nutrient enrichment in promoting **HAB species, Noctiluca and jellyfish.**

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FEATURE ARTICLE

Eutrophication and overfishing in temperate nearshore pelagic food webs: a network perspective

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ABSTRACT: We investigated the effects of human activities on the pelagic food web structure of nearshore marine ecosystems. Their generic structure was established on the basis of literature review and analyzed by qualitative structural network analysis. Two main issues were addressed: (1) the role of species capable of forming harmful algal blooms (HABs) and red tides (*Noctiluca* spp.), as well as the role of jellyfish, in eutrophicated systems; (2) the contribution of human influences on food webs, focusing on bottom-up (increased nutrient loading) and top-down (overfishing) effects. Results suggest that HAB-forming species and *Noctiluca* stimulate the microbial network, but reduce higher trophic levels such as commercially important fish species. Jellyfish act as a buffer in eutrophicated and overfished systems, as they retain nutrients from the water column, but their blooms lead to a massive accumulation of large phytoplankton organisms. Anthropogenic nutrient enrichment favors undesirable species because of their specific position in the food web, and this crucial position may explain their far-reaching effects. Finally, while it appears that overfishing of piscivorous fishes inhibited HABs and supported blooms of diatoms and other large algae in the past, the present-day loss of planktivorous fishes acts synergistically with nutrient enrichment in promoting HAB species, *Noctiluca* and jellyfish. These fundamental constraints, which are inherent in the generic structure of pelagic food webs, thus largely determine community dynamics in marine coastal ecosystems.

KEY WORDS: Food web · Eutrophication · Overfishing · Network analysis · Coastal ecosystem · Indirect effects · Harmful algal blooms · Gelatinous plankton

Eutrophication and overfishing are threatening marine coastal communities worldwide. Visible consequences are harmful algal blooms and jellyfish outbreaks. The analysis of the pelagic food web structure by Vasas et al. (diagrammatically idealized above) helps us to understand the mechanisms by which eutrophication and overfishing can generate ecosystem shifts.

Illustration: Sándor Snepp; background from Google Earth™

INTRODUCTION

Coastal waters receive large amounts of anthropogenic nutrients from domestic and industrial effluents and agricultural runoff. Effects of coastal eutrophication are discernible at all trophic levels (Cloern 2001) and appear as direct and indirect qualitative changes in pelagic food webs, e.g. proliferation of harmful algal blooms (HABs), extinction of species at higher trophic levels, and reduced yields of harvestable fishes and invertebrates. These alterations of the food web struc-

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Decadal Changes in Seabird Foraging Activity, Forage Fish, and Plankton in Cattle Pass, San Juan Islands

Emily S. Runnells

Master of Science

University of Washington, 2014

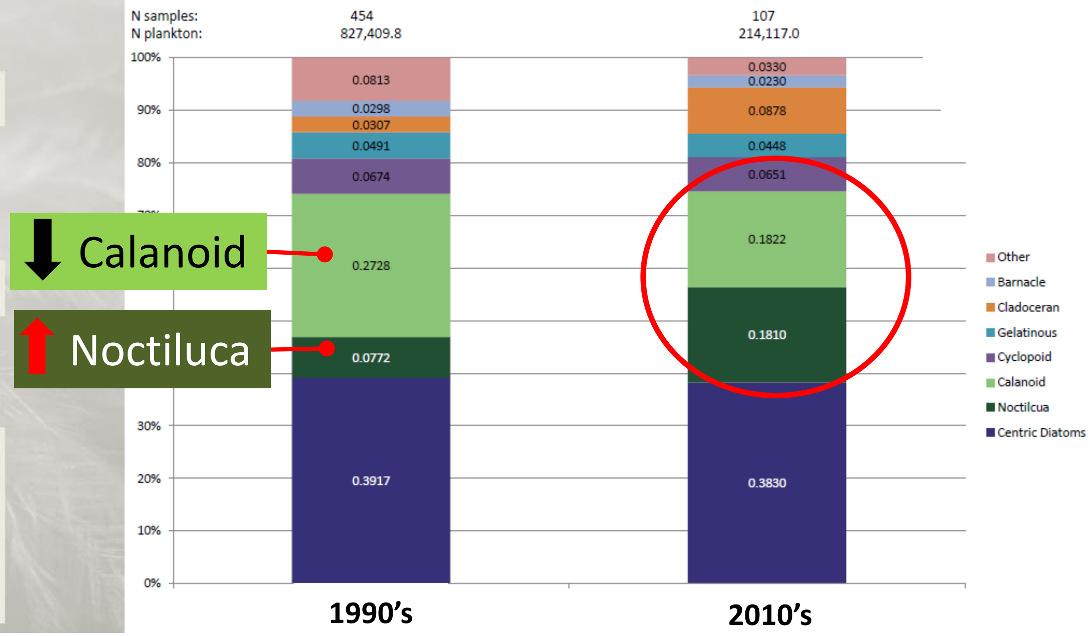
In Conclusion

⬇ **1990s > 2010s**

⬇ **1990s > 2010s**

⬇ **1990s > 2010s for Calanoid Copepods**
Shift in community composition

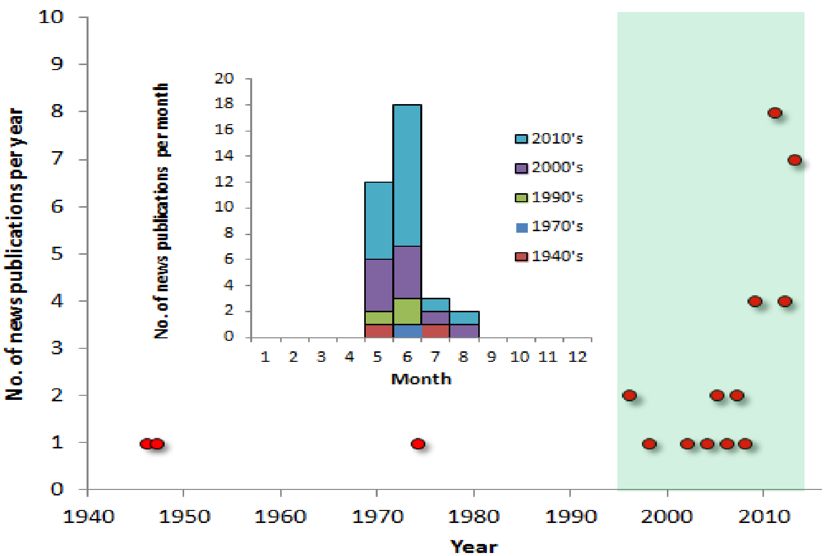
Plankton Community Composition



1) Change not limited to Puget Sound. 2) The effect potentially cascading to higher tropic levels.

HABs blooms and Noctiluca are now frequent in PS

Noctiluca in the local News



State Maximum PSP, ASP Toxin by Year

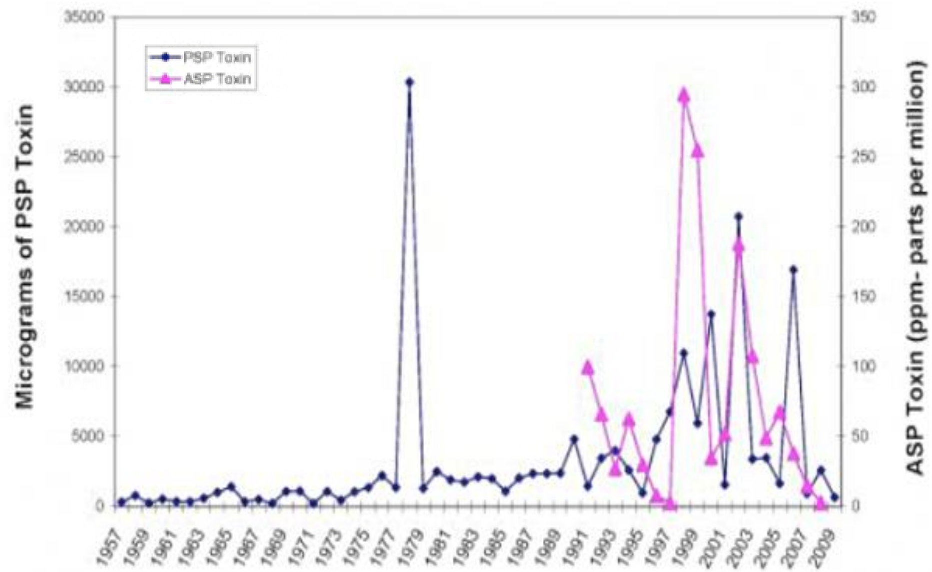
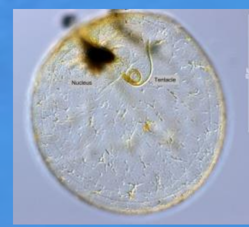


Figure 3. Annual maximum concentrations of PSP and ASP toxins observed in Washington State (WDOH, reprinted from Puget Sound Partnership 2009).

Surface material eventually sinks to the bottom and feeds the benthos. Here, micro-zooplankton grazers do matter!

copepods

micro-grazers
e.g. Noctiluca

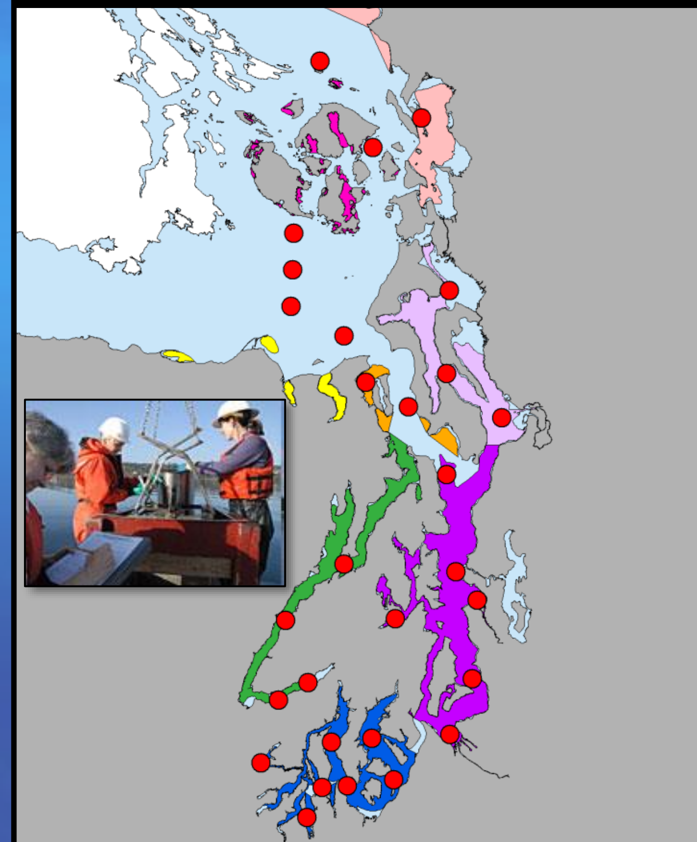


Re-mineralization

Fast-sinking nutrient-rich fecal pellets

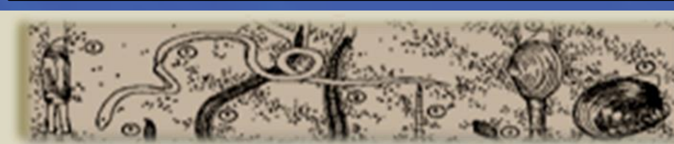
Slow-sinking nutrient-poor loose aggregates

Ecology's Marine Sediment Monitoring Program

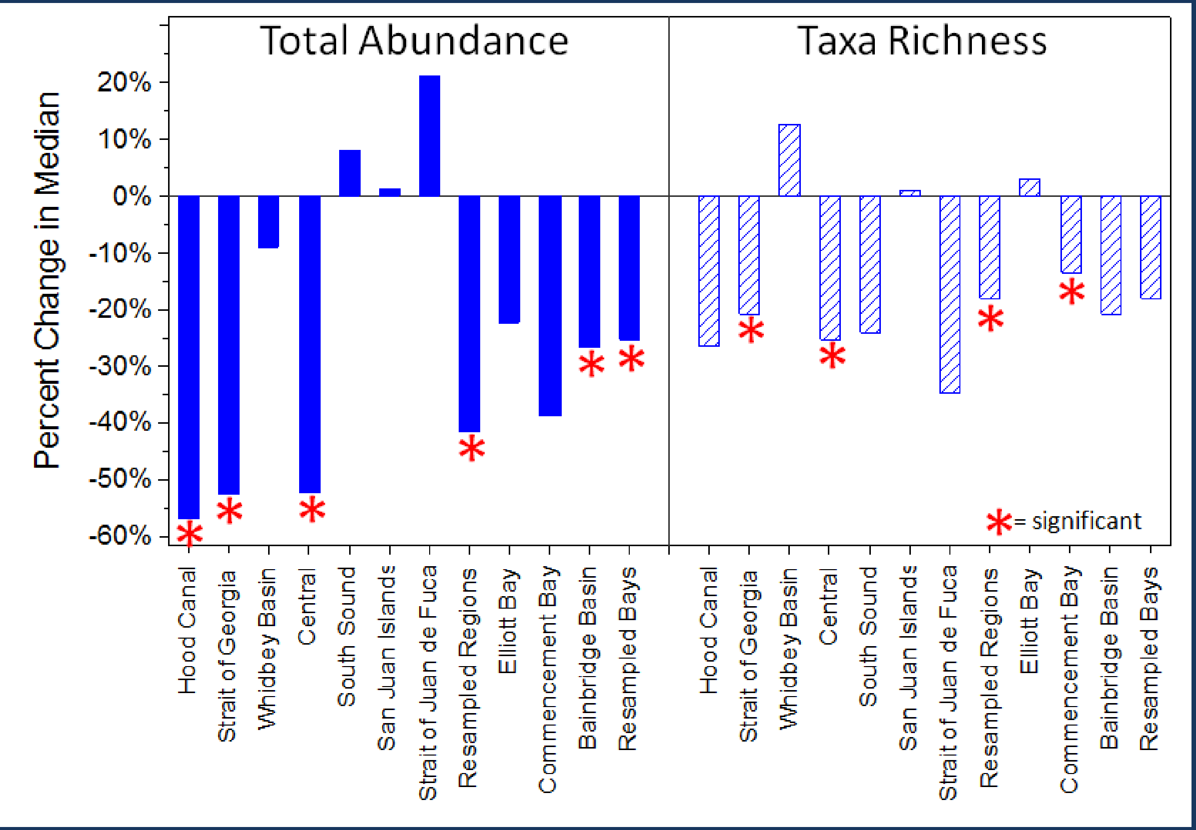


Marine long-term monitoring locations in the greater Puget Sound area (southern Salish Sea). **Colored regions** benthic monitoring regions.

Are micro-grazers changing the organic particle export to the benthos **(the benthic-pelagic coupling)?**



Could micro-grazers change particles from fast-sinking, nutrient-rich fecal pellets to slow-sinking nutrient-poor loose aggregates?



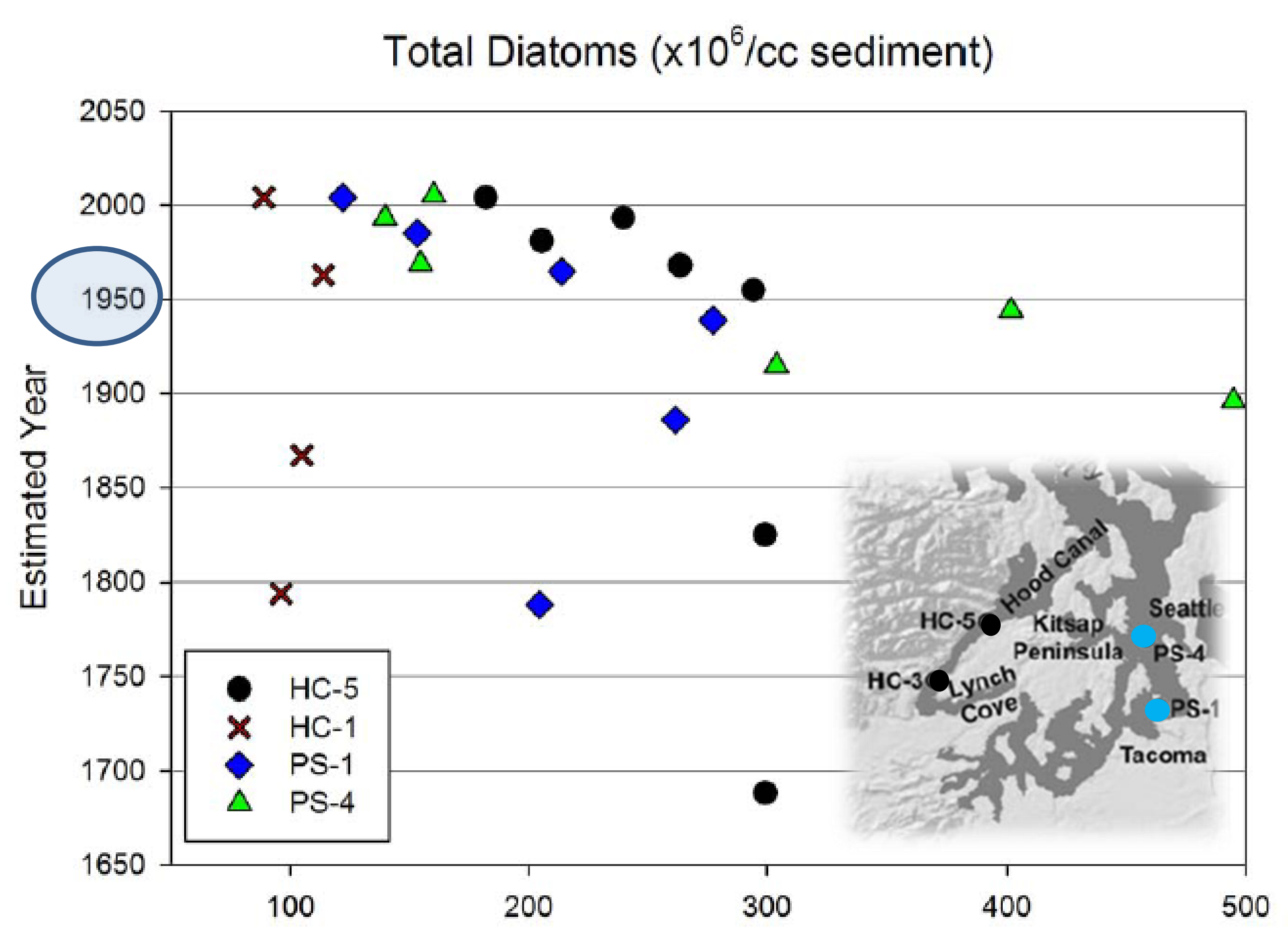
Dutch, Partridge, Weakland. PSEMP Sediment Monitoring: An overview of the program and what's new at the bottom.

- Decadal decline in benthic abundance and taxa richness
- Detritivores most affected

Are these potentially signs of a reduced particle export to the benthos?

Trends in the sediment record before 1999?

Brandenberger et al. 2008



Reconstructing Trends in Hypoxia Using Multiple Paleoecological Indicators Recorded in Sediment Cores from Puget Sound, WA.

NOAA Coastal Hypoxia Research Grant

Report, Figure 39. Diatom valve abundance in each cubic centimeter of wet sediment (shown in millions of valves) for Puget Sound (PS-1 and PS-4) and Hood Canal (HC-1 and HC-5) sediment cores. The y-axis indicates estimated year of samples determined by ^{210}Pb chronology.